TACTICAL AND STRATEGIC LEVEL PLANNING IN FLOAT GLASS MANUFACTURING WITH CO-PRODUCTION, RANDOM YIELDS AND SUBSTITUTABLE PRODUCTS

by

Zeki Caner Taşkın

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ABSTRACT

TACTICAL AND STRATEGIC LEVEL PLANNING IN FLOAT GLASS MANUFACTURING WITH CO-PRODUCTION, RANDOM YIELDS AND SUBSTITUTABLE PRODUCTS

In this study, tactical and strategic level planning problems in float glass manufacturing are investigated. Float glass manufacturing is a continuous process which has some unique properties such as uninterruptible production, random yields, partially controllable co-production compositions, complex relationships in sequencing of products and substitutable products. Furthermore changeover times and costs are very high and production speed depends significantly on the product mix. These characteristics render measurement and management of production capacity a significant task. The motivation for this study is a real life problem faced at Trakya Cam, which is the Şişecam company at flat glass market. Trakya Cam has multiple, geographically separated production facilities and transportation of glass is expensive. Therefore logistics costs are significant. In this work we consider color campaign planning, multi-site aggregate planning and strategic planning problems. We develop a decision support system based on several mixed integer linear programming models in which production and transportation decisions are given simultaneously. The system has been fully implemented and deployed at Trakya Cam. Comparison of production plan generated by our system with manual production plan indicates a significant increase in level of detail that can be handled, an increase in applicability of the production plan in the complex production environment, ability to manage production capacity effectively and a significant decrease in transportation costs without a decrease in the quality of service.

ÖZET

BİRLİKTE ÜRETİM, RASSAL GETİRİ VE İKAME EDİLEBİLİR ÜRÜNLÜ FLOAT CAM ÜRETİMİNDE TAKTİK VE STRATEJİK SEVİYE PLANLAMA

Bu çalışmada, float cam üretiminde taktik ve stratejik seviye planlama problemleri incelenmektedir. Float cam üretimi sürekli süreç tipli bir üretim olup durdurulamayan üretim, rassal getiri, kısmen kontrol edilebilir birlikte üretim kompozisyonları, ürünlerin üretim sıralamasında karmaşık ilişkiler ve ikame edilebilir ürünler gibi özelliklere sahiptir. Ayrıca ürün değişim zamanları ve maliyetleri çok yüksektir ve üretim hızı ürün gamına dikkate değer ölçüde bağımlıdır. Bu özellikler, üretim kapasitesinin ölçülmesini ve yönetilmesini zorlaştırmaktadır. Bu çalışmanın esin kaynağını, Şişecam'ın düz cam grubuna ait Trakya Cam şirketinde karşılaşılan gerçek problemler oluşturmaktadır. Trakya Cam'a ait coğrafi olarak birbirinden uzakta konumlanmış olan birçok üretim tesisi bulunmaktadır ve cam ürünlerinin taşınması maliyetli bir işlemdir. Bu nedenlerden ötürü lojistik maliyetleri dikkate değer ölçüde yüksek olmaktadır. Bu çalışmada renk kampanyası planlaması, çok tesisli toplaşık planlama ve stratejik planlama problemleri ele alınmakta ve karışık tamsayı doğrusal programlama tekniklerini kullanan bir karar destek sistemi tariflenmektedir. Kullanılan eniyileme modelleri üretim ve taşıma kararlarını eşzamanlı olarak vermektedir. Sözü geçen sistem tamamen gerçekleştirilmiş ve Trakya Cam'da kullanıma alınmıştır. Sistemin ürettiği planın planlamacılar tarafından elle üretilen planla karşılaştırılması sonucu, idare edilebilen bilginin detay seviyesinde ciddi bir artma, üretilen planın gerçek üretim ortamının şartlarında uygulanabilir hale gelmesi, üretim kapasitesinin etkin bir şekilde yönetilebilir duruma gelmesi ve taşıma maliyetlerinde dikkate değer bir azalma gibi faydalar gözlemlenmiştir.

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LIST OF SYMBOLS/ABBREVIATIONS

A_{lt}	Available time on production line l at time period t
b_{ic}	Backlog cost for product i for shipment to customer c
B_{ict}	Backlog of product i for customer c at time period t
bs_{ic}	Cost of unsatisfied safety stock for product i for customer c
BS_{ict}	Unsatisfied safety stock of product i for customer c at time t
BT	Index of base thickness group
c	Index for customers
$C(i)$	Coating type of product i (1 if product i is coated, 0 otherwise)
D_{ict}	Demand of customer c for product i at time period t
DR_{ic}	Ratio of demand of customer c for product i to export demand
$E(c)$	Type of customer c (1 if foreign, 0 if domestic)
g	Index for product groups (color, coating, thickness)
$G(i)$	Index of product group for product i
h	Index for thickness groups
h_{ic}	Inventory holding cost for product i for customer c
$H(i)$	Index of thickness group for product i
i	Index for a subset of products in production feasibility set
I_{ict}	Inventory of product i for customer c at time period t
l	Index for production lines
$L(i)$	Indices of production lines that can produce product i
MD_h	Minimum production duration for glass of thickness group h
p	Index for all products (color, coating, thickness, quality, size)
P_{lt}	Production preference on production line l at time period t
$\mathcal{P}$	A subset of products in production feasibility set
q	Index for quality groups
$Q(i)$	Index of quality group for product i
r	Index for colors
$R(i)$	Index of color for product i
R_{lqs}	Maximum ratio of production of quality q and size s on line l

s	Index for size groups
$S(i)$	Index of size group for product i
S_{gl}	Production speed of product group g on production line l
SC_{ls}	Daily stacker capacity for size group s on production line l
SS_i	Safety stock level for product i
t	Index for time periods
T_{iclt}	Production duration of product i for customer c on line l at t
TC_{cls}	Freight cost of size group s from line l to customer c
X_{iclt}	Production quantity of product i for customer c on line l at t
Y_{hlt}	Indicator variable for products with thickness h on line l at t

CRT	Cathode ray tube
R&D	Research and development

1. INTRODUCTION

In this thesis, tactical and strategic level production planning problems in float glass manufacturing are studied. Float glass manufacturing is a continuous process type production governed by complex relationships between products. There are some major characteristics of float glass production that are not commonly observed in other production environments:

- The process is continuous and production cannot be interrupted.
- Yields are random due to random errors scattered on glass surface resulting from processes that are not fully controllable.
- The process is of co-production type, meaning that several products must be produced simultaneously by the nature of the process. Furthermore, type and ratio of the products produced simultaneously is not fixed but can be changed within some bounds. In this aspect, the co-production structure in float glass manufacturing is different from other co-production environments in which type and ratio of co-products are usually fixed.
- Products are substitutable in the sense that demand for a lower quality product can be satisfied by a higher quality product.

The motivation of this study is a real life problem faced at Trakya Cam, which is the Şişecam Group company in flat glass market. Şişecam is a group involved in production of glass and related products. It was founded in 1935 in order to meet glass requirements of Turkey and has dominated the domestic market in glass products since. Currently, it is among the leading glass manufacturers in the world with several production facilities and a wide range of products. The group has operations in several segments:

- **Flat glass:** A wide range of products including float glass, figured glass, automotive glass, laminated glass, mirror, tempered and coated glass are produced by the Şişecam group company Trakya Cam.

- **Glassware:** Several products for personal use and decoration are produced by the group company Paşabahçe Cam.
- **Glass packaging:** Glass packaging materials such as glass bottles are produced by the group company Anadolu Cam.
- **Chemicals:** Raw materials and chemicals for glass production such as sand, soda ash, limestone are produced by the group company Soda Sanayii.

Trakya Cam is the only national flat glass manufacturer. It is also among the top five flat glass manufacturers in Europe and top ten in the world [1]. The firm has several facilities producing different types of flat glass products:

- **Float glass:** Float glass is produced from raw materials such as sand, soda ash, limestone etc. and is used directly in several industries such as construction industry. Furthermore, it is the main raw material for other flat glass processing industries. Trakya Cam has two float glass facilities at Lüleburgaz and Mersin. Two new facilities at Bulgaria and Bursa are under construction. Float glass production is a process type production, details of which are discussed in Section 2.2.
- **Automotive glass:** Automotive industry requires high quality glass produced by special processes. Trakya Cam has an automotive glass production facility at Lüleburgaz, which uses float glass as raw material and supplies customized products to most automotive manufacturers in Turkey.
- **Processed glass:** Glass products are used in many industries, which have different needs based on areas of application. Tempered glass is used in fridges, ovens, shower cabins etc. Coating is a chemical process applied to change thermal properties of glass for use in heat and solar control applications. Trakya Cam has a glass processing plant at Çayırova, which uses float glass as the main raw material, cuts it in customized shapes and applies required processes.
- **Mirror and laminated glass:** Mirror is mainly used in furniture and laminated glass has applications in security related fields. Float glass is the main raw material for both products: mirror is formed by coating one side of float glass with metal and laminated glass is formed by combining two sheets of float glass

under high temperature and pressure with PVB in between. Trakya Cam has a mirror and laminated glass plant at Lüleburgaz.

One problem within Trakya Cam is that sales and marketing personnel do not understand the complex production process completely and cannot predict results of the co-production structure. For example, receipt of an order for a significant amount of Product A results in an increase in production of Product A. However, Product A cannot be produced alone without accompanying Product B and Product C. Therefore, production of Product A results in an increase in production of Product B and Product C as well. However, since the increase in Product B and Product C production is not foreseen by the sales staff, inventory accumulates for Product B and Product C. Later, sales department tries to sell the accumulated inventory for Product B and Product C by offering promotions etc. Therefore sales activities without consideration of the co-production structure result in a decrease in profits.

Trakya Cam currently has two facilities that can produce float glass at different rates. These facilities are geographically sparse and transportation costs are significant. Unique characteristics of float glass manufacturing make measurement of "capacity" difficult and possible amount of production depends significantly on the product mix. Therefore planning staff cannot define exact capacities of facilities and analyze various tradeoffs in capacity planning. Simple rules based on past experience are used for allocating customer demands to facilities. Since transportation costs are not explicitly considered during production planning, logistics costs are high. The situation is expected to worsen when the two new facilities currently under construction become operational.

In float glass production, capacity cannot be expanded by overtime or subcontracting. The only way to expand production capacity is building new facilities. Building a new facility takes up to two years and costs approximately $120 million [1]. Locations of facilities determine transportation costs. Therefore timing, location and amount of capacity expansion are important strategic decisions that affect future profitability seriously. Long term marketing decisions regarding capacity allocated to domestic and foreign markets are also parts of the strategic planning problem. These decisions require detailed analysis of production capacity and evaluation of tradeoffs between various scenarios.

In this thesis a mathematical programming based decision support system for solving central planning problems faced in a multi-site float glass manufacturing environment is described. Float glass is the main raw material for other flat glass products. Therefore production planning of float glass facilities affects the entire flat glass supply chain. There are three major problems considered in this work:

- *Campaign Planning:* Colored glass is produced in one or two campaigns per year due to high changeover costs involved. Therefore, campaign planning is important for inventory management of colored glass. We describe a mixed integer programming model for determining optimal duration and product mix of campaigns in Section 4.4.
- *Multi-Site Aggregate Planning:* Obtaining a production plan which is feasible under unique properties of float glass manufacturing and which minimizes transportation costs is a difficult problem. Production planners make certain simplifications and disregard some constraints in order to keep the problem at a manageable size. These simplifications result in infeasibilities in the resulting plan as well as high logistics costs. We describe a multi objective mixed integer programming model that determines optimal production plan considering production capabilities, inventory and backlog costs along with transportation costs in Section 4.5.
- *Strategic Planning:* We describe a mixed integer programming model that facilitates fast and reliable scenario analysis in strategic planning in Section 4.6. The model also aids in setting long term marketing goals regarding capacity allocated to domestic and export markets.

The system we describe in this thesis has been fully implemented and deployed at Trakya Cam. It helps decision making in sales, production and logistics planning: In our models, unique production characteristics of float glass manufacturing are modeled as constraints. Hence production plans generated are applicable in the production environment. An output of the model related to sales planning is identification of demand that cannot be satisfied by available production capacity. Similarly, production capacity not allocated by existing demand forecast is determined and is used for guiding sales. The system also considers logistics issues by allocating customer demand to production facilities in such a way that transportation costs are minimized. Therefore the main purpose of this study is to develop a mixed integer linear programming based decision support system that unifies sales, planning and logistics decisions.

The rest of the thesis is organized as follows: Basic definitions are given in Section 2.1. An overview of float glass production is given in Section 2.2 followed by a more detailed look in Section 2.3. Planning issues are discussed in Section 2.4 and some simplifying assumptions are stated in Section 2.5. A survey of existing literature on production planning is given in Chapter 3. Mixed integer linear programming models for campaign planning, multi-site aggregate planning and strategic planning are developed in Chapter 4. Implementation issues are discussed in Chapter 5. Comparison of the new system with previously employed spreadsheet based manual planning process is given in Chapter 6 and results obtained are discussed. Finally, conclusions and future research directions are identified in Chapter 7.

2. PROBLEM DEFINITION

In this section we describe the planning problem in float glass manufacturing. We first give definitions of the basic terminology used throughout the thesis in Section 2.1. Later, we describe the major operations in float glass manufacturing in Section 2.2. We later discuss important properties of the process such as co-production, random yields, high changeover costs etc. that need to be considered during planning in Section 2.3. After discussing issues regarding planning such as product substitution, campaign planning, effect of cutting policy employed etc. in Section 2.4, we give some simplifying assumptions and discuss their validity in Section 2.5.

2.1. Float Glass Definitions

- **Float:** Float is a process for producing glass in which raw materials such as sand and soda ash are liquefied and the solution floats over liquid tin to gain a smooth surface. Details of the process are given in Section 2.2.
- **Coating:** Coating is a chemical process in which one surface of float glass is covered with very thin layers of metal. Depending on types of metals used, visual and thermal properties of glass can be enhanced. It is possible to apply basic coating during float glass production (Section 2.2) where more complicated coating processes are applied in a separate facility (Chapter 1).
- **Product groups:** Product groups are identified by color, thickness and coating type of glass. Color types that float glass is produced are: clear, green, blue, fume and bronze. Thickness varies in the range [2.00 - 19.00] mm and glass can be produced as coated or not coated.
- **Products:** Products within a product group are identified by size and quality of glass. The three main size groups are:
  - Jumbo size (2800 – 3260 x 3600 – 6000) mm^2
  - Machine size (2800 – 3260 x 1000 – 2700) mm^2
  - Split size (600 – 2100 x 1400 – 2500) mm^2

As it can be seen, jumbo size is approximately two times larger than machine size and machine size is approximately three times larger than split size. Quality of glass is measured by type and number of defects on glass surface. An example of a stock keeping unit (SKU) is clear, 4 mm, coated, jumbo size, K1 quality glass [2].

2.2. Overview of Float Glass Production

Float glass is produced on continuous production lines, length of which exceed one kilometer. Production lines operate independent of one another. Raw materials undergo several operations consecutively in order to form end products (Figure 2.1 [3]):

- **Melting:** Production on each line starts by mixing raw materials in appropriate amounts and feeding into glass furnace. The furnace heats raw materials up to 1600°C where raw materials melt down to form liquid glass. Color of the glass can be changed at this stage by adding some colored raw materials into the mixture poured into the furnace.
- **Floating:** After a few hours in the furnace during which the liquid glass homogenizes, liquid glass moves on to the next phase where it floats over liquid tin. This is the phase in which glass is formed into a smooth surface. Thickness of the glass is adjusted at the end of this phase.
- **Coating:** Glass with desired color and thickness undergoes an optional coating phase at which glass is coated with chemicals in order to enhance thermal properties. Coating type of the glass is determined at the end of this phase. In other words, product groups are identifiable at the end of coating phase.
- **Annealing:** This is the phase in which temperature of glass is decreased gradually down to ambient temperature. This phase has no significance from the viewpoint of production planning.
- **Cutting:** The process is continuous from beginning of melting to end of annealing. Quality of glass is inspected continuously by an optical laser system and glass is cut into desired size by cutting machines and is collected by stacking machines based on size and quality groups. In other words, size and quality of glass

is determined at the end of cutting phase and products are identifiable. This phase has important implications regarding production planning and is detailed in Section 2.3.

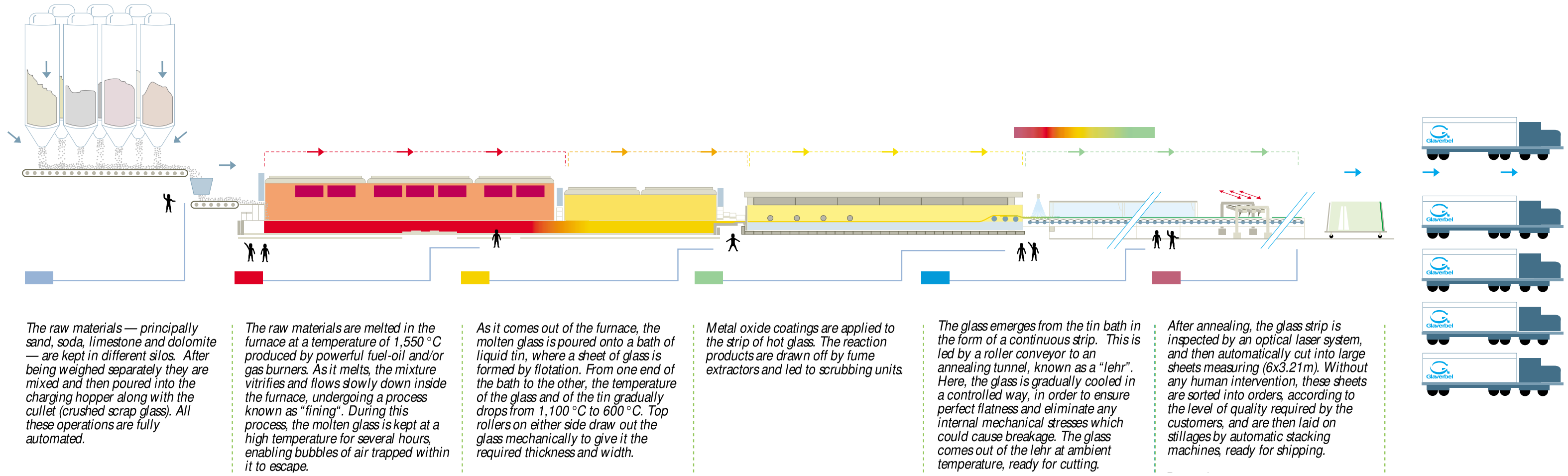


Figure 2.1. Production of float glass

2.3. Issues in Float Glass Production

Property 1. *Float glass production is a continuous process in which production cannot be stopped.*

Float glass manufacturing is a continuous process in which production continues 24 hours a day, 365 days a year. It is not possible to stop the glass furnace that melts raw materials to produce liquid glass. The reason is that, if the furnace is stopped glass freezes inside the furnace and the furnace has to be rebuilt from scratch. Therefore production has to continue throughout the lifetime of the furnace, which is typically over 10 years. Production cannot be interrupted even if process quality is not under control, in which case nonconforming glass is broken and scrapped at the end of the production line.

Property 2. *There exist parallel production lines with different production capabilities and capacities.*

In float glass manufacturing, alternative lines can produce the same product at different rates. For example clear glass can be produced on all available production lines but only some lines are capable of producing colored glass. Similarly very thin or thick glass can only be produced on some lines. In other words, production capabilities of production lines are different in terms of types of products that can be produced on each production line and production speeds.

Property 3. *Changeover costs associated with color changes are very high.*

In order to produce colored glass, some extra raw materials are melted in the furnace. Therefore, desired color is achieved gradually as liquid glass within the furnace becomes a homogeneous solution. Furthermore, color changeover times between different colors are sequence-dependent. For example switching from clear to fume takes about three days while the opposite takes about seven days. During color changeover, entire production is nonconforming and is scrapped.

Currently there are four production lines satisfying entire float glass demand in

Turkey and a significant percentage of production is exported. In other words, color changeover in a production line is equivalent to a 25% loss in overall production capacity for up to a week's time. Therefore changeover costs are very high.

Property 4. *Coated glass can only be produced during daytime.*

Coating is a chemical process which requires daylight and hence can only be performed during daytime. Since production cannot be stopped, glass with the same color and thickness is produced during nighttime. Therefore, there are limits on coated glass that can be produced and interactions between production of coated and not coated glass exist.

Property 5. *Thickness changeover can only be performed on a continuous scale.*

Since glass production is a continuous process, thickness changeover has to be performed gradually. In other words, if glass with any two different thickness values is to be produced, glass with all thickness values in between needs to be produced as well. Thickness changes on a continuous scale, it is not possible to make discrete "jumps" from one thickness value to another. Furthermore, thickness has to be adjusted slowly since fast changes destabilize the process. In order to allow for stabilization of the process, thickness has to be kept constant at some levels for some minimum duration.

Thickness changeover also has associated costs. As discussed, thickness changes on a continuous scale but thickness groups that can be sold are on a discrete scale. For example, assume that allowed specification range for 3 mm glass is $[2.80 - 3.20]$ mm and that for 4 mm glass is $[3.80 - 4.20]$ mm. Further assume that currently the process is stabilized at thickness 3 mm. Adjusting target thickness value to 4 mm results in production of glass in the range $[3.00 - 4.00]$ mm. Among the glass produced during thickness changeover, glass with thickness in range $[3.00 - 3.20]$ mm can be sold as 3 mm and glass with thickness in range $[3.80 - 4.00]$ mm can be sold as 4 mm. However, glass with thickness in range $(3.20 - 3.80)$ mm is nonconforming and has to be scrapped. Time during which production is nonconforming can be regarded as changeover time and production scrapped can be considered as changeover cost associated with thickness change. It should be noted that thickness changeover time is quite short compared to color changeover time: changeover time for color is on the order of days while changeover time for thickness is on the order of hours.

Property 6. *Multiple products have to be produced simultaneously due to random errors scattered on glass surface.*

Float glass production involves complex physical and chemical processes, some of which are not well understood or are not fully controllable. This results in random errors scattered throughout glass surface. There are several types of error, ranging from tiny visual disruptions to serious errors that necessitate glass to be scrapped. Since float glass is used in many industries, some errors that are unacceptable for some applications can be disregarded for some other applications. For example, allowances for mirror and automotive glass are much tighter than those for window glass and glass to be further processed for use in ovens. The diversity in tolerances results in definition of several quality groups based on number and type of errors allowed.

Glass is transformed gradually from raw materials into liquid glass and then solid glass at ambient temperature and the production line processes the entire spectrum at all times. In other words, glass at the end of annealing phase forms a “river of glass”, which originates from beginning of the production line and runs continuously for years. Glass surface is continuously observed by an optical laser system located before cutting machines. Coordinates and types of nonconformities are determined instantly and processed by a software system controlling cutting machines. When a nonconformity is detected, cutting policy is changed and glass is collected as lower quality and/or in smaller size. This is how **co-production** is encountered in float glass production: non-controllable errors in process results in simultaneous production of several products. Distribution and density of random errors determine maximum possible amount of production for each quality and size group.

A hypothetical situation is constructed in order to clarify the situation: Figure 2.2 shows a small portion of glass coming from the production line. Glass surface has been scanned by the optical laser system and an error has been designated by X. Assume X is out of tolerance limits for glass of quality level K1, but is acceptable for quality level K2. Location of cutting machines and direction of movement are also shown.

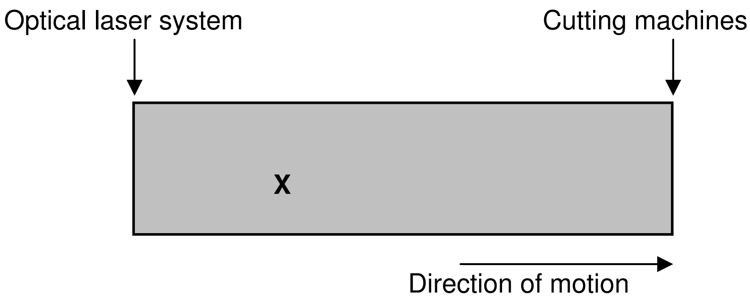
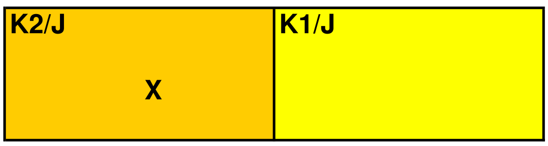


Figure 2.2. Sample of error distribution on glass at the end of production line

Figure 2.3 shows result of cutting glass in jumbo size. The glass sample is cut into two equal pieces. Since one of the pieces contains an error designated by X, it is of quality K2 and the other one is of quality K1. Therefore, two end products are produced from the glass sample in equal amounts. Ratio of K1 quality glass produced is 0.50.



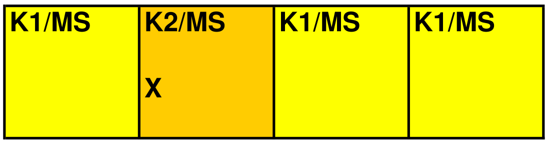
Product	Quantity	Ratio
K1/J	1	0.5
K2/J	1	0.5

Figure 2.3. Cutting policy 1

Figure 2.4 shows result of cutting glass in machine size. Here, the glass sample is cut into four equal pieces. Since one of the pieces contains an error designated by X, it is of quality K2 and the others are of quality K1. Therefore, two end products are produced from the glass sample and ratio of K1 quality glass produced is 0.75.

This simple example illustrates a few key points about float glass production:

- Existence of random errors on glass surface necessitates co-production of multiple



Product	Quantity	Ratio
K1/MS	3	0.75
K2/MS	1	0.25

Figure 2.4. Cutting policy 2

products.

- Quantity and type of end products depend on the cutting policy employed.
- Quality and size of end products are interdependent.

Property 7. *Availability of stacking machines limit number and type of products that can be produced simultaneously.*

After cutting at the end of production line, glass is collected by automated stacking machines and laid on stillages for packaging. Each stacking machine can only be used to collect glass of a specific dimension; it is not possible to collect jumbo size glass on a machine size stacking machine or vice versa. Stacking machines have a cycle time consisting of the time required to collect glass, move it into required position, lay on stillage and then return to idle status. Machines cannot be assigned a new task unless they are idle. Therefore, there's a limit on availability of each stacking machine based on its cycle time. This is another source of co-production: even if surface of the glass produced contained no random errors, the fact that stacking capacity for each size group is limited would necessitate simultaneous production of glass within several size groups. Therefore, even if glass surface were perfect, several products would be produced simultaneously.

Only one type of product can be collected by a stacking machine at any time. Therefore, number of products within each size group that can be produced simultaneously is bounded by the number of stacking machines available for that size group. A cutting policy with respect to the set of products that are produced simultaneously is referred as a **composition**.

Property 8. *Compositions are realized at the operational level by a priority list of products.*

Available stacking machines are assigned specific products, hence quality and size groups. The software system controlling cutting machines is given a **priority list** consisting of products and the stacking machine each product is assigned to. The software system reads distribution of errors on glass surface from the optical laser system. Given the error distribution, the system then cuts the glass in such a way that the product with the highest priority compatible with error distribution is collected by the assigned stacking machine.

Working mechanism of the priority list can be described on the hypothetical example given in Property 6. Given the error distribution shown in Figure 2.2, assume that the priority list consists of K1/J and K2/J, respectively. In this case, the software system responsible for controlling cutting machines first checks whether the immediate portion of glass of jumbo size is compatible with quality level K1. Since the right hand side half of the glass sheet does not contain any defects, it is of K1 quality level and the system decides to cut one sheet of K1/J glass. Then given this decision, it checks whether the remaining portion of glass is suitable for collecting K1/J glass. However, the second half contains a defect and cannot be collected as K1. Since the top priority item cannot be produced given the current error distribution, the software system moves on to the second item in the priority list, which is K2/J. This time the system checks whether the remaining portion of glass can be collected as K2/J. Since the second portion contains only one defect, it is compatible with K2 quality level and the second half of glass is collected as K2/J. The result of this composition is shown in Figure 2.3. Similarly, Figure 2.4 shows the result obtained by adding K1/MS and K2/MS glass to the priority list under the same error distribution. In this case, the first two pieces are collected as the top priority product K1/MS, the third piece of glass is collected as K2/MS and the last piece is collected as K1/MS.

In general there exists a configuration of the priority list for each composition and compositions are uniquely identified by priority list configurations. Configuration of the priority list determines the types of end products produced as well as their ratios.

A stacking machine is assigned to each item in the priority list. Therefore total number of items in the priority list cannot exceed the number of stacking machines (Property 7) for each size group. Each stacking machine can be assigned a quality group or can be disabled. Therefore, total number of possible priority list configurations is $s^{(q+1)}$ where s is the number of stacking machines and q is the number of quality groups. It should be noted that a significant portion of these configurations is "redundant". For example, the priority list that contains K2/MS and K1/MS in given order is equivalent to the priority list that only contains K2/MS. The reason is that, since K1 quality level also satisfies requirements of K2 quality level and K2 has higher priority, it is not possible to collect K1 in this composition. Therefore K1/MS is "redundant", *given* K2/MS as a higher priority item.

Sequencing of priority lists is also an issue. Since the production is continuous, it is not possible to make "jumps" between priority lists. A stacking machine cannot be assigned a new product unless its stillage is full. The reason is that, glass is broken during transportation if stillage is not fully loaded. Hence, priority list can only be changed when one of the stillages is full, in which case assignment of only the corresponding stacking machine can be changed. Therefore only one item can be different between adjacent priority lists. Furthermore, the time each stillage gets full is a random variable depending on the instantaneous error distribution. Therefore it is not possible to determine sequence of priority lists to be used deterministically.

2.4. Planning Issues in Float Glass Production

Property 9. *Production capacity cannot be adjusted through overtime, undertime or subcontracting.*

The fact that stopping production is not an option (Property 1) results in inevitable inventory accumulation for time periods in which capacity exceeds demand. Furthermore, expanding production capacity by means of overtime or subcontracting is not possible. This results in possible stock-out for time periods in which demand exceeds capacity. Therefore, available capacity can be considered as a "given fact" and inventory planning is important in order to minimize inventory costs and satisfy demand in periods in which demand exceeds capacity. All production lines have to be fully utilized in a feasible production plan.

Property 10. *Production capacity depends significantly on the product mix.*

Existence of multiple production lines on which products can be produced at different rates (Property 2) introduces alternative selection as an important issue in planning. On average production speed for newer lines is approximately 10% higher than older lines. Similarly, glass with different thickness values can be produced on the same line but production speed for glass of medium thickness is approximately 35% more than that for thin glass. Production capacity depends significantly on both production lines and product groups. Therefore, capacity cannot be defined independent of the product mix.

Property 11. *Safety stocks are kept for products.*

As discussed in Property 1 production cannot be stopped and inventory accumulates in periods in which demand is low. Since holding inventory is unavoidable by the nature of the process, the main issue in inventory planning is not reducing inventory costs by avoiding inventory. The issue is giving inventory decisions correctly so that service level is maintained at satisfactorily high values. Furthermore, since production plans are based on imperfect forecast information, it is desired to keep safety stocks in order to guard against fluctuations in demand. The safety stock strategy employed is a dynamic one in which it is desired to have inventory level at the end of a period no less than some percentage of demand in the next period.

Property 12. *Products can be substituted for lower quality products within the same size and thickness group.*

Required quality levels of end products demanded by customers depend on area of application. Quality groups are defined based on number and types of random errors allowed on glass surface (Property 6). Therefore, quality groups are cascaded in the sense that glass which satisfies requirements of a higher quality group also satisfies requirements of a lower quality group. For example, glass containing no errors can be classified to be within K1 quality group which allows for a small number of insignificant errors. On the other hand, it also satisfies requirements of K2 quality group which allows for more number of errors on glass surface. In general, glass of quality group i satisfies requirements of quality groups j where $j \geq i$.

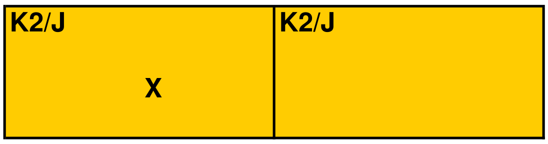
From a demand satisfaction point of view, customers demanding glass of a specific size and quality are equally happy with glass with the same size and better quality. Therefore, demand is **substitutable**. However, demand substitution is not applicable to products with different dimensions. In this work only we only consider demand substitution within products with the same thickness value. However, some customers demanding glass of some thickness value could be equally happy with glass of close thickness values. Consideration of cross-sales between different thickness values could be beneficial for profitable operation in forecasting, planning and sales. This point is further discussed as a future research direction in Chapter 7.

One possible way to deal with demand substitution and random errors in production would be to collect glass within each quality and size group independent of others. In this approach, glass within each quality and size group would be collected separately and demand satisfaction decisions could be made after production. In other words, demand satisfaction decisions would be made "offline", *given* realized production quantities. However, since only one type of product can be collected at each stacking machine (Property 7), this approach would require simultaneous operation of *number of quality groups* stacking machines for each size group. However, only two or three stacking machines are available for each size group. Similarly total number of stacking machines required would be: *number of quality groups* x *number of size groups*, which is much greater than available number of machines. Therefore this approach is not applicable in general.

Another approach, which is employed at Trakya Cam is to make demand substitution decisions "online" during production. Compositions are realized by priority lists of products at operational level (Property 8). Each item in the priority list is assigned a stacking machine. Therefore total number of stacking machines in use at any time is bounded by the number of stacking machines for each size group (Property 7). Usage of priority lists results in implicit product substitution: products which are not in the priority list and hence are not collected by stacking machines in their actual quality categorization are automatically substituted for products with lower quality that are in the list. For example if the top priority item in the list is of quality group K2, all glass of quality K1 - which also satisfies requirements for quality group K2 - is also collected as K2. In other words, K1 quality glass is substituted for K2 quality glass.

The two approaches differ fundamentally with respect to their approaches to product substitution and quality management. In the first approach, products with similar *physical* quality characteristics in terms of distribution of errors are collected and stacked together into the same stillages. Hence, quality management and demand substitution are based on **physical quality**. On the other hand, products with different physical quality characteristics can be stacked together into the same stillages in the second approach. However, once glass with several quality specifications are packed together, it is no longer possible to differentiate between them. In the example above, even if glass of quality group K1 and K2 are mixed together within stillages, it is not possible to separate glass of *physical quality* K1 from glass of *physical quality* K2. So, quality of the entire stillage becomes essentially K2. Quality management and product substitution are based on **effective quality**, which depends on quality levels of sheets of glass that are stacked together. In other words, physical quality of the glass is the result of random errors in non-controllable processes while effective quality of glass can be changed by planning.

The ideas of product substitution and effective quality can be demonstrated visually on the hypothetical example discussed in Property 6. Given the same error distribution in Figure 2.2, adding only the product K2/J to the priority list and assigning only one stacking machine results in production shown in Figure 2.5. This policy is equivalent to cutting all glass in jumbo size and substituting K1 glass for K2 glass. As it can be seen, only one end product - K2 glass of jumbo size - is produced. The first piece contains a defect marked by X. Therefore both physical quality and

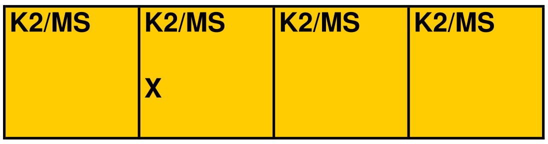


Product	Quantity	Ratio
K2/J	2	1

Figure 2.5. Cutting policy 3

effective quality for the first piece are K2. The second piece does not contain any defects and therefore is of physical quality K1. However, since it is stacked onto a stillage together with pieces of quality K2, its effective quality is K2. In other words, glass of physical quality K1 is *substituted* for glass of physical quality K2.

Similarly, Figure 2.6 shows the result of adding only the product K2/MS to the priority list and assigning only one stacking machine:



Product	Quantity	Ratio
K2/MS	4	1

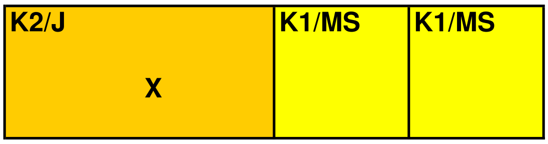
Figure 2.6. Cutting policy 4

Here, only machine size glass of quality K2 is produced and glass of physical quality K1 is *substituted* for glass of physical quality K2.

Property 13. *Cutting policy employed determines types and quantities of end products obtained significantly.*

Determining cutting policy is an important planning decision. Although random errors on glass surface limit possible production of each product (Property 6), the fact that demand is substitutable within the same size group (Property 12) allows for application of several cutting policies. Furthermore, it is always possible to cut glass of each size and quality group as several pieces of glass of smaller size and at least the same quality group.

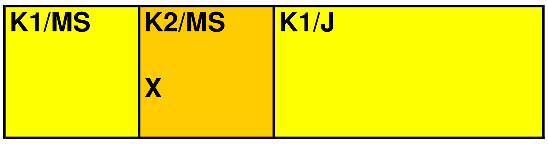
Figure 2.7 shows the result of cutting two machine size pieces of quality level K1 instead of the jumbo piece of quality level K1 in Figure 2.3.



Product	Quantity	Ratio
K1/MS	2	0.5
K2/J	1	0.5

Figure 2.7. Cutting policy 5

Figure 2.8 shows the result of cutting two machine size pieces instead of the jumbo piece of quality level K2 in Figure 2.3. It can be seen that it is possible to cut two machine size glass within quality groups K1 and K2 instead of a single jumbo within size group K2.



Product	Quantity	Ratio
K1/J	1	0.5
K1/MS	1	0.25
K2/MS	1	0.25

Figure 2.8. Cutting policy 6

The joint effect of surface errors, product substitution and cutting size determination is shown on Figure 2.9. It can be seen that even for this simple case where only two size and quality groups are considered and there exist only one nonconformity on glass surface, total number of cutting policies in which entire glass production is collected as end product is at least seven. Therefore compositions need to be considered during production planning and the issue is one of the most interesting issues in float glass manufacturing.

Property 14. *Colored glass is produced in campaigns.*

As discussed in Property 3, color changeovers have high associated costs and hence color changeovers need to be planned carefully. Since changeover costs are much more expensive than holding inventory, colored glass is produced in campaigns in order to minimize changeovers. A typical campaign may consist of successive production of clear, light green, dark green, blue and clear glass. Depending on demand patterns,

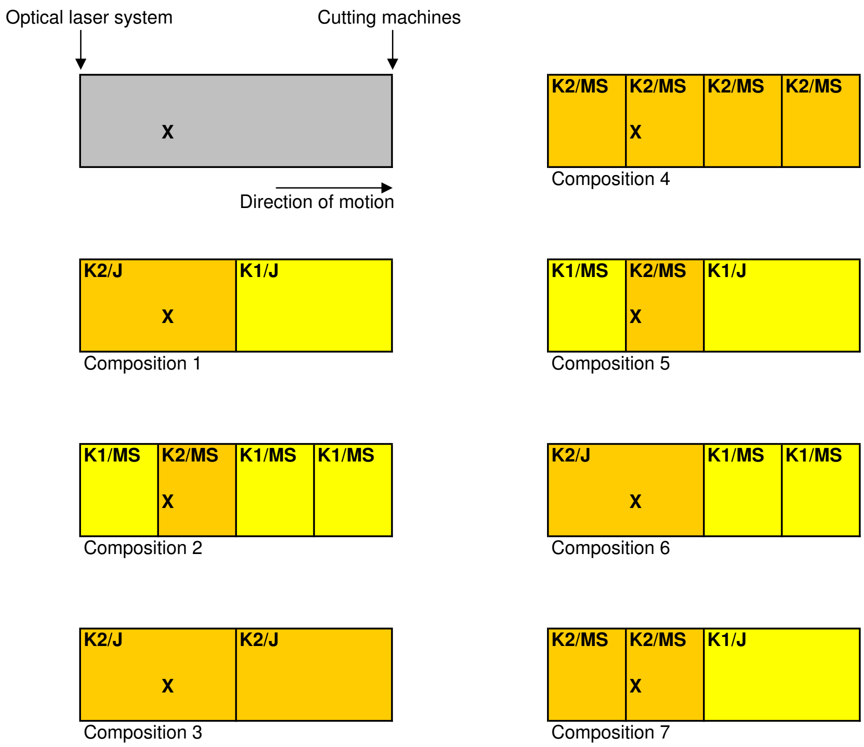


Figure 2.9. Compositions

glass of each color is produced in one or two campaigns a year. Planning process is hierarchical in the sense that first color campaigns are planned on a yearly basis and then thickness and coating are planned on a monthly basis [2].

Campaign planning is essential for inventory management of colored glass. The main idea behind a campaign is accumulating enough inventory at the end of the campaign so that entire demand until the next campaign can be satisfied from inventory. It should be noted that this does not necessarily mean making production for all demand between specified periods; demand can also be satisfied from initial inventory. There are several issues regarding campaign planning:

- *Timing of campaigns:* Since each product has a different initial inventory level and a different demand structure, the time in which initial inventory is depleted can be different for each product. This is the time before which additional production needs to be planned in order to avoid out-of-stock for the product. In the case of colored glass, the minimum of such time values for all products with the specified color corresponds to the latest time a campaign needs to be planned for that particular color.

- *Sequencing of colors within campaigns:* Since changeover times between colors are sequence dependent (Property 3), sequencing of colors within campaigns should be determined in such a way that the total changeover time is minimized.
- *Duration of campaigns:* Duration of each campaign must be long enough so that all demand for products for time periods before the next campaign on the same color is satisfied. Furthermore, minimization of duration is desired in order to avoid accumulating excessive inventory. All other properties of float glass production are also valid for colored glass production. Especially composition (Property 13), product substitution (Property 12) and thickness related issues (Property 5) complicate campaign planning. Therefore finding minimum duration of campaigns in which demand for all products within the colors produced during the campaign under production constraints is a difficult optimization problem.
- *Planning multiple campaigns:* Products with some colors facing rather high demand are produced in more than one campaign per year. For those, timing of the second campaign is an issue. In this case interactions between campaigns need also to be planned. If the first campaign satisfies demand of all products until the second campaign and yet more products need to be produced due to compositions, the co-products should be chosen among those that have demand after the second campaign, if possible. Otherwise, the co-products produced in the first campaign need to be held in inventory for a long time while the second campaign needs to be extended in order to satisfy demand.

Property 15. *There exist multiple production sites and transportation costs are significant.*

Trakya Cam sales department is located at Şişecam headquarters in İstanbul. Also, production and logistics planning are performed in headquarters while planners at production facilities are responsible of operational planning and scheduling. Demand is received centrally and sales, production planning and logistics departments need to coordinate their actions in order to satisfy demand. Most float glass demand in Turkey is satisfied by Şişecam and products are exported to several countries worldwide.

Therefore, customers are geographically sparse and various transportation methods are used. Production planning department decides on production plans for facilities and the facility from which demand of each customer is to be satisfied. Currently there are two float glass production sites within Şişecam Group at Lüleburgaz and Mersin, which are approximately 1000 kilometers apart. Two new facilities at Bulgaria and Bursa are under construction. (Figure 2.10). Transportation of glass is quite expensive and logistics costs are significant since glass is a fragile material and it can easily be broken during transportation. Hence specialized equipments are used in transportation of glass. For example jumbo size glass is transported by specially manufactured trucks.

Figure 2.10. Facility locations

Property 16. *Timing, location and amount of capacity expansion are crucial.*

Şişecam expects continuous growth in both domestic and foreign markets, resulting in increasing demand. In order to meet the increase in demand, capacity needs to be expanded. In our problem overtime, undertime or subcontracting are not possible (Property 9). Therefore the only way to expand capacity is to build new facilities. However production cannot be stopped throughout the lifetime of the furnace (Property 1). Hence, if capacity is expanded early, capacity exceeds demand, resulting in inventory build-up which needs to be sold by means of promotions. On the other hand, if capacity is expanded late demand exceeds available capacity and cannot be satisfied. Furthermore, locations and production capabilities of new facilities need to be carefully planned in order to minimize expected costs (Property 15). For example if demand of clear glass in domestic markets is expected to increase, building a new facility within Turkey reduces transportation costs while choosing dedicated technology that can only produce clear glass reduces investment costs. Capacity expansion decisions need to be given early facing significant uncertainty since it usually takes up to two years for a new facility to become operational. Long term sales & marketing planning is also a part of strategic planning: the strategy employed by Şişecam is to satisfy domestic demand completely and allocate remaining production capacity to exports. This couples marketing and capacity expansion decisions: marketing goals affect new facility locations and capacity allocations while available facility capacities and product mix affect marketing goals.

Property 17. *Multiple objectives need to be considered during planning.*

Properties of float glass production discussed above need to be considered in production planning in order to obtain a realistic plan in terms of feasibility. Backlogs are allowed only when production capacity is insufficient to satisfy demand. Under these conditions, the goals of production planning in order of priority can be identified as:

- Obtaining a feasible production plan in terms of production capacity and various interactions between products.
- Satisfying demand as long as production capacity permits, hence minimizing backlogs.
- Minimizing costs incurred by transportation activities.
- Determining production quantity and product mix so that inventory carrying costs are minimized and appropriate amount of safety stocks are kept.

2.5. Assumptions

In order to build a model that can be solved within reasonable time and yet that is an adequate representation of the inherent complexity, we make some simplifying assumptions:

Assumption 1. *Thickness changeover can be performed between adjacent thickness groups on a discrete scale.*

In float glass production thickness can only be changed over on a continuous scale (Property 5). In our model, it is assumed that thickness changeover can be performed between adjacent thickness values given on a discrete scale. These discrete values correspond to those thickness values at which a minimum amount of production has to be performed in order to allow for stabilization of process during thickness changeover.

Assumption 2. *There exists a thickness value that corresponds to a significant percentage of demand.*

Our model is based on a discrete time scale where thickness changeovers can take place on a continuous time scale in float glass production. In real production environment, it is possible to end a period at any thickness value and begin the next period at the same thickness value. However, sequencing of thickness values is beyond the scope of this thesis. The reason is that, time frame for thickness sequencing is on the order of days while length of time periods we deal with is months for aggregate planning and years for strategic planning. Here, it is assumed that production on each line in each period starts and ends at a specific thickness value that is referred as **base thickness value**. This assumption is based on the observation that ratio of demand for glass of 4 mm thickness is approximately 60 % of total demand.

Assumption 3. *Glass can only be cut in dimensions on a discrete scale.*

There is a wide range of dimensions that can be produced and product dimensions can be given on a continuous scale (Section 2.1). Here, it is assumed that only discrete size groups can be demanded by customers and produced by production lines. An example of size groups are: jumbo, machine size and split size groups.

Assumption 4. *Changeover time associated with thickness changeover is negligible.*

Although thickness changeover has associated changeover time and cost (Property 5), it is assumed that thickness changeover time is negligible from the perspective of aggregate production planning. This assumption is based on the fact that changeover time for most thickness changes is on the order of hours.

3. LITERATURE SURVEY

In this section, we present relevant literature on production planning issues. We propose a classification scheme of the literature and discuss similarities and differences between our work and existing literature. In a production environment facing fluctuating demand, several strategies can be employed to meet the demand with limited production capacity [4]:

- Adjusting production level through overtime/under time
- Adjusting workforce level through hiring/firing
- Using subcontracting to delegate production
- Holding inventory / backlogging demand

Each of these strategies has benefits as well as associated costs. Aggregate Production Planning Problem (APP) can be defined as finding the best combination of these strategies to match supply and demand with minimum cost. The APP has been widely studied since 1950s and several techniques have been developed. Although APP is an optimization problem by nature, early work focuses on heuristic methods and simulation. A survey of non-optimal methods such as linear decision rule, search decision rule, management coefficient and simulation based methods is given in [4]. Only after the enormous increase in computational power in the last decade, optimization based methods have become a feasible alternative for large scale real world applications.

Several approaches addressing different aspects of the problem in various industries have been proposed. Although many classification schemes can be proposed, we discuss existing literature in the following groups:

- *Basic Models:* We regard models concerned with single-facility production planning in discrete production environments where parameters are known with certainty as basic models. Models for production planning in various industries, multi-objective models and work on mathematical formulation techniques are discussed in Section 3.1.

- *Multi-Site Planning:* Extensions of basic models in horizontal and vertical supply chains in which transportation costs become an issue are discussed in Section 3.2.
- *Production Planning in Process Industries:* Process industries have several differences from discrete industries regarding production planning. Issues in planning in process industries and related literature are discussed in Section 3.3
- *Strategic Planning and Planning Under Uncertainty:* Most long term decisions need to be given facing significant uncertainty and decision makers need to manage risk. Strategic planning issues in several industries and mathematical techniques for handling uncertainty are discussed in Section 3.4.

3.1. Basic Models

Production planning is a difficult problem especially in industries where the production process is complex and product diversity is high. For example, TV production is an assembly type process which requires simultaneous availability of hundreds of components manufactured in several facilities with different production types. The final product can be assembled using alternative sub-assemblies and on alternative assembly lines. Production speed varies by both product type and assembly line. Semiconductor manufacturing requires hundreds of operations [5]. Some of these operations are reentrant, meaning that semi-products visit the same machinery several times during production. Generally newer machinery work faster and can perform operations with more precision while older machinery are slower and less precise. Therefore some operations can be performed only on newer machinery where others can be performed on both new and old machinery with different rates. In such environments even finding a feasible solution can be an issue. “Capacity” needs to be defined and managed carefully since number of products processed can depend significantly on product mix.

Basic models in aggregate planning assume that demand, capacity requirement and production yields are deterministic and aim to find the optimal way of utilizing limited capacity to fulfill anticipated demand. A decision support system called Capacity Planning Optimization System (CAPS) has been implemented at a semiconductor facility of IBM [5]. CAPS is a linear programming based decision support system that can be used to plan production and identify bottleneck resources given demand for products. Furthermore, by relaxing demand constraints more profitable product mixes that are achievable using available capacity can be searched.

Different mathematical formulations for production planning problem and effect of solution techniques has been investigated in the literature [6]. Size of production planning problem instances tend to grow quickly as more details such as alternative machine types, lead times and unique production constraints are incorporated into models. Furthermore, most real world applications require modeling of hundreds of products and machine types, setups etc. resulting in large scale mathematical models [7]. As the dimensional and structural complexity increases, required computational power for solution increases. Therefore, compact formulations are required to solve larger problem instances within an acceptable time. Several formulations for capacity modeling with alternative machine types are given and compared with respect to number of constraints, decision variables and nonzero elements in [6]. There are several algorithms for solving linear programs including Simplex, Dual Simplex, Karmarkar's Algorithm, Barrier Methods etc. which have different characteristics in terms of convergence speed. Several equivalent LP formulations for supply chain planning are given and effect of formulation and solution algorithms on solution time is investigated in [7].

Usually decision makers consider several objectives such as minimization of late orders, maximization of profitability and minimization of changes in workforce level simultaneously. An extension to basic models account for multiple objectives. Goal programming based approach is discussed in [4] and applications of multiple objective models in construction [8] and chemical [9] industries have been reported.

In our problem alternative production lines for product groups exist with different production rates (Property 2). Capacities of stacking machines at the end of production lines impose further constraints on quantity and type of products that can be produced (Property 7). Color changeover in production requires takes significant time and colored glass is produced in campaigns (Property 14). One of the differences between our model and existing literature is that each production line must run continuously and production cannot be interrupted (Property 1). Furthermore, changing production level by means of undertime/overtime or subcontracting is not possible. Therefore among the strategies for handling fluctuating demand discussed above, only keeping inventory/backlogging can be employed. This low "degree of freedom" in planning decisions, combined with unique characteristics of production makes the planning problem in float glass manufacturing a difficult one.

3.2. Multi-Site Planning

Multi-site production can be regarded as a generalization of alternative machinery in which products can be manufactured in alternative production sites. As in the case of alternative machinery, production sites may have different production capabilities and capacities which need to be considered during planning. Furthermore, production costs can vary significantly between sites, especially if sites are located in different countries.

Implementations in several industries are reported in the literature: A basic model consisting of decision variables for overtime production, subcontracting, hiring and laying off work force, which has been applied at an international lingerie producer is described in [10]. A model that aims to maximize discounted after tax profit of an international pharmaceutical company is discussed in [11]. The company modeled in [11] has sales offices and production sites in several countries. Sales prices, production costs, tax rates and interest rates differ by region and optimal production plan for each site is sought. For supply chains in which production sites are geographically diverse, transportation costs become significant [12]. In such cases, giving production and transportation decisions simultaneously gives better results than giving decisions sequentially [13]. An extension that accounts for customers' preferences in cases where more than one production sites can produce for the same market is given in [14]. An interesting feature in the model discussed in [14] is that it can handle different time scales for production and sales. This feature is based on the observation that time scale used for demand forecasts usually has less granularity than the one used for production plans: For example, demand forecasts can be given as “items per month” where production decisions are given as “items per week”.

Capacity planning issues in supply chains in vertical direction have not been investigated in detail. In a single-level supply chain, facilities manufacturing end products behave as alternatives to one another and total capacity of the supply chain is the sum of capacities of facilities. However in a multi-level supply chain, capacity of the supply chain is determined by the level with minimum total capacity. A mixed integer nonlinear programming model which addresses multiple levels in capacity planning is described in [15].

Multi-site capacity expansion and planning problem is discussed in a distributed decision making framework in [16]. The authors observe that in large multi-site organizations, capacity expansion decisions are usually given at headquarters, production decisions are given by production planning departments and decisions related to order receipt and delivery are given at sales & marketing departments. A distributed decision making framework based on this observation is proposed. Several decomposition algorithms supporting the framework are designed and tested in terms of solution quality and computational complexity.

In our model multiple production sites with different production capabilities and capacities are considered (Property 15). Logistics costs are explicitly taken into consideration. Furthermore, safety stocks kept in order to control stock-out risk are modeled. The model developed has multiple objectives regarding demand satisfaction, transportation costs and inventory management (Property 17).

3.3. Production Planning in Process Industries

Process industries have several characteristics that separate them from discrete manufacturing industries. The fundamental difference is that production is continuous in process industries meaning that products flow continuously rather than in discrete lots [17]. Semi-products and raw materials are mixed in continuous quantities. This makes it difficult to associate production with customer orders and make-to-stock approach is employed in many process industries. Usually it is not possible to store intermediary products by the nature of process. Special storage requirements may exist for both raw materials and end products: items may be perishable and usually only one type of product can be stored at each storage facility at any time. Furthermore, inventory space is physically bounded by capacity of storage facilities. Setup times are usually very significant since production and / or storage facilities need to be cleaned before starting production of another item and initial production needs to be scrapped until the process stabilizes. These and similar characteristics need to be considered in capacity planning. Furthermore, equipments and machinery investments are typically capital intensive and subcontracting is not an option. Hence, capacity management is important in order to operate under a profitable product mix. Several approaches to production planning in the process industry are discussed in [17].

An important distinction between discrete manufacturing and process industry is about definition of products: in discrete manufacturing, product specifications are usually defined with certainty. Product design is completed before planning and the design is considered as given during planning. Although some alternatives can be considered during planning, usually the set of alternatives is a discrete, finite set. For example, several cathode ray tubes (CRT) can be used in production of a television and choice of CRT is an important planning decision. Yet, CRT is the only optional component among dozens of items assembled. On the other hand, in many process industries end products are not defined by exact specifications. Usually more general definitions about minimum and maximum ratios are set on some attribute values [17]. In other words, product design can be regarded as an integral part of planning since any production resulting in a product within specification limits is acceptable [18]. This possibility allows for choice of production and routing based on availability of raw materials and associated costs. Problems of blending type are encountered in many industries: an application in energy industry about coal planning is discussed in [18]. In the model described in [18], several power plants have unique specifications on coal they can burn. Coal can be acquired from several sources, each having unique characteristics and associated costs. Also, blending facilities have production capabilities regarding types of coal used. The problem is finding an optimal blending plan considering coal specifications, power plant requirements, blending facility capacities and associated costs. A mixed integer programming formulation and a heuristic solution algorithm are developed.

Another characteristic that complicates planning is the interactions between products [19]. In one type of interaction, some kinds of products need to be produced before or after some others. In another type of interaction, namely co-production or by-production, process results in simultaneous production of more than one product. Therefore, production decisions on interacting products cannot be given independently and interactions between products need to be modeled explicitly. In some cases process is not well understood or cannot be kept under precise control. This results in random yields meaning that quantity to be scrapped is random and in some cases the same product having several quality specifications can be produced simultaneously. In this case a customer requesting a product with a specific quality can be equally satisfied by the same product with a higher quality level and demand is said to be substitutable. A problem in semiconductor industry is described in [19]. Production of semiconductors is the result of a complex series of operations, some of which are not well understood. Because of the randomness in the process, individual items produced within a batch can behave differently. Products can be grouped into several groups based on their performance. Customer orders can be satisfied by products with better performance than requested. Hence demand is substitutable, co-products exist and yield is random. The problem is decomposed into two phases: "morning" phase where production lot size is determined and "afternoon" phase where production is completed and items are grouped with respect to their performance. In the "afternoon" phase, the issue is matching required shipments with available products and deciding on demands to be satisfied by overqualified products. A dynamic programming model and several heuristic methods are described [19].

Float glass manufacturing is a continuous process and shares similar characteristics with other process type industries: color changeover takes a significant time and glass produced during color changeover, which can take up to a week, is scrapped (Property 3). Similarly, some amount of glass needs to be broken during a changeover in thickness. Several interactions between products exist: for example, it is not possible to produce thin and thick glass consecutively, some glass of medium thickness has to be produced in between (Property 5). Similarly, coating is a chemical process that requires sunlight and cannot be performed at night. Therefore production of coated glass is accompanied by production of not coated glass (Property 4). Complex co-production relationships regarding size and quality of glass produced exist (Property 6). Furthermore yields are random due to random errors on glass surface (Property 6) and demand is partially substitutable (Property 12). The problem discussed in [19] resembles our problem but:

- In [19] items produced in the same batch differ only by quality groups and items with higher performance can be used for satisfying demand for lower performance. Therefore items within the highest quality group are substitutes to all others. However, in our model products differ by both quality and size. Substitution is allowed only for items within the same size and thickness groups. For example, demand for K4 / jumbo size glass can be substituted by K1 / jumbo size glass but not by K1 / machine size glass.
- In [19], co-production rates are totally random; quantities of end products follow a probability distribution. However, in our system co-production rates are partially controllable. For example it is always possible to cut glass as two pieces of machine size glass instead of a single piece of jumbo size glass. The partial control on production composition is the most significant issue that makes planning in float glass manufacturing both interesting and difficult.
- In [19], the problem is decomposed into “morning”(lot sizing) and “afternoon” (demand satisfaction) phases. Lot sizing decisions are given before production considering probabilistic nature of production and demand structure. Demand satisfaction decisions are given after production is completed, hence with full information about yields. However in float glass manufacturing, such a decomposition is not possible: There’s no lot sizing decision since the process is continuous and production cannot be stopped. Furthermore demand satisfaction decisions

need to be given online before cutting and collecting the final product. Once glass is collected, it cannot be used to satisfy demand for other sizes.

- In [19], a dynamic programming model is developed and several heuristics for approximate solutions are given while we propose a mixed integer linear programming model that can be solved optimally.
- In [19], the problem is formulated for a single site while our model is multi-site with explicit consideration of transportation costs.

3.4. Strategic Planning and Planning Under Uncertainty

Strategic planning is a critical issue in many organizations due to the long term effects involved. Decisions such as capacity expansion, new facility investment, new product and technology development are capital intensive and have a great impact on future profitability. Due to associated lead times in realization of investments, these decisions need to be made quite early, often facing significant uncertainty. For example in the pharmaceutical industry, research and development (R&D) is a time consuming process in which it can take up to 10 years for a successful drug to be publicly available [11]. Many potential drugs are eliminated in several clinical tests. However, it is usually too late to decide on capacity investment after successful clinical tests due to the long investment lead time and the limited patent lifetime. Therefore capacity decisions need to be made before completion of clinical tests when it is unknown whether the drug will succeed. Tool capacity planning in semiconductor industry is a similar problem in which demand for products is highly volatile and many products require specialized, custom built tools which have long procurement lead time and are usually expensive [16]. The decision for capacity expansion has to be made long before demand is realized [20]. If future demand realizes but the capacity has not been expanded, it may not be possible to satisfy demand, resulting in lost sales. On the other hand, if capacity has been expanded and demand does not realize the resources dedicated to capacity expansion are wasted [21]. Therefore the decision for capacity expansion given uncertain demand involves risk by nature and it has important long term consequences [22]. Type of technology invested in new capacity is also an important strategic decision [23]. Facilities dedicated to a specific product group usually require less capital investment and operate more efficiently than flexible facilities. However, dedicated facilities may become a liability if demand for their designated product groups turns out to be low.

Decision makers facing uncertainty often work with several scenarios like "most likely", "optimistic" and "pessimistic" and try to investigate effects of decisions in alternative scenarios [23]. Deterministic models discussed above can be used for what if analysis on alternative scenarios. In this approach a solution is found for each scenario, which is optimal for that scenario only and suboptimal in other scenarios. Furthermore, how to "combine" optimal solutions for several scenarios into a single decision is not clear. Several approaches have been proposed for dealing with this problem. The reader is referred to [24] for a recent survey on optimization under uncertainty. We introduce basic techniques here.

Stochastic programming is one of the most widely used methods for planning under uncertainty. In two stage stochastic programming models, first stage variables correspond to those decisions that are given under uncertainty while second stage variables model decisions given after the first stage decisions when the uncertainty is resolved. For example in the capacity expansion problem in semiconductor industry first stage variables correspond to the number new machinery to be acquired and second stage variables correspond to amount of production, given demand scenario and decision made for number of new machinery acquired [21]. Given probabilities of occurrence for each scenario, the model finds a solution which is feasible for all scenarios and minimizes expected cost for all scenarios. It should be noted that usually the solution found by stochastic programming is not optimal in any of the scenarios but represents a "hedged" decision. The two stage stochastic program can be modeled as linear, mixed integer or nonlinear programs. A shortcoming of stochastic programming is that size of the mathematical program to be solved is linearly proportional to the number of scenarios. This limits use of mixed integer programming and nonlinear programming based stochastic programming approaches due to excessive computational requirements. However, it is shown in [22] that working with a set of demand scenarios by stochastic programming results in more efficient solutions than working with a single scenario based on optimistic demand for products. A similar analysis on "value of stochastic solution" are reported in [23].

Other approaches to planning under uncertainty include fuzzy mathematical programming [25] and Markov decision problems [9]. In fuzzy mathematical programming, random parameters are treated as fuzzy numbers and constraints are treated as fuzzy sets. A multi-objective fuzzy program for aggregate production problem that minimizes the most possible value of the imprecise total costs, maximizes the possibility of obtaining lower total costs, and minimizes the risk of obtaining higher total costs is formulated in [25]. A capacity expansion and technology selection problem similar to the one faced in pharmaceutical industry [11] is discussed and modeled as a Markov decision process in [9]. In the model, capacity can be expanded using an available technology or the expansion can be delayed until adoption of an experimental technology. Completion time for R&D efforts for the new technology is a random variable and the new technology is expected to reduce operating costs once it is available. However, it might fail tests as well. The challenge faced by decision makers is whether to expand capacity using existing technology and accept the risk of working inefficiently in case the new technology is adopted; or waiting for adoption of the new technology and accept the risk of the technology failing tests. The state space of Markov decision process is defined to be the cartesian product of adoption of technology and capacity expansion in several time periods. Although the novel approach to strategic planning provides useful insights, its excessive computational requirements render it impractical for large scale real world cases.

In float glass manufacturing, the only way to expand capacity is building new facilities. Timing, location and amount of capacity expansion are important decisions that affect future profitability. Furthermore, long term demand planning in terms of capacity allocated to domestic and foreign markets is a part of strategic planning (Property 16). In this thesis, we develop a mixed integer linear programming model that can be used for evaluating various scenarios in Section 4.6 and identify extension of the model by stochastic programming concepts as a future research direction in Chapter 7.

4. MATHEMATICAL MODEL

In this section, we develop a mathematical model for production planning in float glass manufacturing. We first define a **production feasibility set** (σ) which determines the set of feasible production plans for a given list of products under production capabilities discussed in Section 2.3 and Section 2.4. We later use the production feasibility set as a black-box for campaign planning, multi-site production planning and strategic planning. The underlying production environment is the same for all three planning problems. Therefore they are similar in terms of production feasibility but have quite different planning objectives.

4.1. Definition of Symbols

Symbols used in our model and their brief definitions are:

Indices:

r	Index for colors
g	Index for product groups (color, coating, thickness)
p	Index for all products (color, coating, thickness, quality, size)
i	Index for subset of products for which production feasibility set determines the set of feasible production plans
l	Index for production lines
c	Index for customers
t	Index for time periods
q	Index for quality groups (sorted in descending order of quality)
s	Index for size groups (sorted in descending order of size)
h	Index for thickness groups (sorted in ascending order of thickness)
$G(i)$	Index of product group for product i

$H(i)$	Index of thickness group for product i
$Q(i)$	Index of quality group for product i
$S(i)$	Index of size group for product i
$R(i)$	Index of color for product i
$C(i)$	Coating type of product i (1 if product i is coated, 0 otherwise)
$E(c)$	Type of customer c (1 if customer c is foreign, 0 if customer c is domestic)
$L(i)$	Indices of production lines that can produce product i
$\mathcal{P}$	A subset of products for which production feasibility set determines the set of feasible production plans

Parameters:

D_{ict}	Demand of customer c for product i at time period t (Unit: ton)
DR_{ic}	Ratio of demand of customer c for product i to entire export demand (Used in strategic planning)
SC_{ls}	Daily stacker capacity for collecting glass of size group s on production line l (Unit: ton / day)
SS_i	Safety stock level for product i as a ratio of demand in next period
S_{gl}	Production speed of product group g on production line l (Unit: ton / day)
TC_{cls}	Cost of transporting glass of size group s from production line l to customer c (Unit: \$ / ton)
MD_h	Minimum production duration for glass of thickness group h (Unit: day)
A_{lt}	Available time on production line l at time period t (Unit: day)
BT	Index of base thickness group
R_{lqs}	Maximum possible ratio of production of quality group q and size group s on line l
P_{lt}	Preference of production of on production line l at time period t (Used in campaign planning)

b_{ic}	Backlog cost for product i for shipment to customer c
bs_{ic}	Cost of unsatisfied safety stock for product i for shipment to customer c
h_{ic}	Inventory holding cost for product i produced for customer c

Decision variables:

T_{iclt}	Production duration for product i for shipment to customer c on production line l at time period t (Unit: day)
X_{iclt}	Production quantity for product i for shipment to customer c on production line l at time period t (Unit: ton)
I_{ict}	Inventory of product i produced for shipment to customer c at the end of time period t (Unit: ton)
B_{ict}	Backlog of product i produced for shipment to customer c at the end of time period t (Unit: ton)
BS_{ict}	Unsatisfied safety stock of product i produced for shipment to customer c at the end of time period t (Unit: ton)
Y_{hlt}	Indicator variable for production of products with thickness h on production line l at time period t

Before giving mathematical models we need to explain the reason why production, inventory and backlog variables have customer index. The reason is that, products have several packaging types based on customer requests. Furthermore, customers give exact size specifications within a size group. For example although the length of glass within jumbo size group is assumed to be 6 m, some customers can request 5.80 m while some others can request 5.90 m. Therefore in physical production environment inventory for most customers are kept separately as in our model.

4.2. Production Constraints

In this section we develop constraints that define relationships between decision variables and parameters described above.

4.2.1. Mathematical Constraints

Equation 1. *Production speed*

Production speed for all products within a product group on the same line is the same and is given by S_{il}. Equation 4.1 relates production durations to production quantities. The constraint is written for all products, customers, production lines and time periods.

$$X_{iclt} = T_{iclt}\ S_{G(i)l} \qquad \forall(i \in \mathcal{P}, c, l, t) \tag{4.1}$$

Equation 2. *Inventory balance*

Equation 4.2 is the inventory balance equation. It accounts for available inventory and backlog by considering total production on all production lines and demand. It is written for all products, customers and time periods.

$$I_{ic(t-1)} - B_{ic(t-1)} + \sum_{l \in L(i)} X_{iclt} - D_{ict} = I_{ict} - B_{ict} \qquad \forall(i \in \mathcal{P}, c, t > 0) \tag{4.2}$$

Equation 3. *Safety stock*

Safety stocks are kept for products in order to protect against errors in forecasts and unexpected demand fluctuations (Property 11). In our model, levels of safety stocks for products are not fixed quantities but are represented as a ratio of demand in next period. Equation 4.3 accounts for satisfaction of safety stock levels and is written for all products, customers and time periods.

$$I_{ic(t-1)} \geq D_{ict}\ SS_i - BS_{ic(t-1)} \qquad \forall(i \in \mathcal{P}, c, t > 0) \tag{4.3}$$

Equation 4. *Existence of production for thickness groups*

Equation 4.4 forces value of the indicator variable Y_{hlt} to 1 if production for glass of thickness group h is planned on production line l in time period t. Since total production time on a production line in a time period is bounded by total available time, A_{lt} is used instead of an arbitrary large number M in order to obtain tighter bounds and avoid numerical problems. The equation is written for all thickness groups, production lines and time periods.

$$\sum_{i:\ H(i)=h} \sum_{c} T_{iclt} \leq A_{lt}\ Y_{hlt} \qquad \forall(h,l,t) \qquad (4.4)$$

4.2.2. Business Model Constraints

Equation 5. *Production line capacity*

Production cannot be interrupted in float glass manufacturing (Property 1). Therefore all production lines should be fully utilized in a feasible production plan. However, it is important to identify how much capacity is required to satisfy a given amount of demand and what percentage of available capacity is used for producing products without corresponding demand in capacity analysis. Therefore, the production feasibility set has two modes in terms of production line capacities: In STRICT mode, each production line is fully utilized by the following constraint:

$$\sum_{i} \sum_{c} T_{iclt} = A_{lt} \qquad \forall(l,t) \qquad (4.5)$$

On the other hand, under utilization of production lines is allowed in RELAX mode:

$$\sum_{i} \sum_{c} T_{iclt} \leq A_{lt} \qquad \forall(l,t) \qquad (4.6)$$

Equation 6. *Requirement of daylight for coating*

Coated glass can only be produced during daytime (Property 4). In aggregate planning, this means that total production time of coated glass cannot exceed half of the available production time and can be modeled by the following constraint:

$$\sum_{i} \sum_{c} C(i)\ T_{iclt} \leq 0.5\ A_{lt} \qquad \forall(l,t) \qquad (4.7)$$

Even though this formulation is correct regarding total production of coated glass, it is inadequate in modeling the coupling of glass produced during daytime and during nighttime: When coated glass is produced during daytime, glass with the same thickness is produced during nighttime. However, not coated glass can also be produced during daytime. In aggregate terms, this means that total production of not coated glass is no less than total production of coated glass for each thickness group:

$$\sum_{i:\ H(i)=h} \sum_{c} (1 - C(i))\ T_{iclt} \geq \sum_{i:\ H(i)=h} \sum_{c} C(i)\ T_{iclt} \qquad \forall(h, l, t) \tag{4.8}$$

The constraint is written for all thickness groups, production lines and time periods. It should be noted that Equations 4.6 and 4.8 imply Equation 4.7: Since sum of coated and not coated glass has to be less than or equal to the total available time by Equation 4.6 and sum of not coated glass has to be more than or equal to sum of coated glass by Equation 4.8, ratio of coated glass to total production cannot exceed 0.5. Therefore Equation 4.7 is redundant and is not considered any further.

Equation 7. *Gradual thickness changeover*

Thickness of glass has to be changed over gradually on a continuous scale (Property 5). In our model, we assume that thickness changeover can be performed between adjacent thickness groups on a discrete scale (Assumption 1). Furthermore since sequencing thickness values is beyond the scope of this thesis, we further assume that there exists a base thickness value represented by BT such that production on each line at each period starts at this thickness value (Assumption 2). Based on these assumptions, feasible production plans have a special structure regarding thickness groups: If production for any thickness group h is planned, productions for all thickness groups between h and BT have to be planned too. We enforce this structure as a combination of two constraints:

$$Y_{hlt} \geq Y_{(h+1)lt} \qquad \forall(h \geq BT, l, t) \tag{4.9}$$

$$Y_{(h+1)lt} \geq Y_{hlt} \qquad \forall(h < BT, l, t) \tag{4.10}$$

Equation 4.9 ensures that if production is planned for any thickness group above BT, production should also be planned for the adjacent thickness group with smaller index. This condition is enforced on all thickness groups above BT and recursively ensures that if any thickness group above BT is produced, all thickness groups including BT are produced. Equation 4.10 handles the symmetric case for thickness groups below BT. These equations are written for all production lines, thickness groups and time periods.

Equation 8. *Minimum production durations for thickness groups*

Thickness of glass has to be kept constant at some values for some minimum duration in order to allow for stabilization of the process during thickness changeover (Property 5). Equation 4.11 ensures that if glass of thickness h is produced, duration of production is at least MD_h. It is written for all production lines, thickness groups and time periods.

$$\sum_{i:\ H(i)=h} \sum_{c} T_{iclt} \geq MD_h \; Y_{hlt} \qquad \forall (h, l, t) \qquad (4.11)$$

Equation 9. *Limitations on stacking machine capacity*

Stacking machines used for collecting glass into stillages have limited capacity (Property 7). Equation 4.12 limits production of glass within each size group by corresponding stacking machine capacity. It is written for all production lines, size groups and time periods.

$$\sum_{i:\ S(i)=s} \sum_{c} X_{iclt} \leq A_{lt} \; SC_{ls} \qquad \forall (l, s, t) \qquad (4.12)$$

Equation 10. *Compositions*

The fact that glass surface contains random errors (Property 6), combined with the possibility of substituting products (Property 12) results in production in various compositions (Property 13). Compositions are realized by priority lists at the operational level (Property 8). One way to model compositions in production planning could be based on priority list configurations. Ratio of products co-produced when cutting machines are operated under a particular priority list can be estimated statistically. Therefore, production quantities for co-products when a particular priority list is operated for a time period can easily be modeled by a linear constraint. Under this setting, production duration for each priority list could be a decision variable instead of production duration for each product. However, there are a few issues about **priority list based composition modeling**:

- Co-production ratios of products within a priority list can be modeled as discrete values based on statistical estimates. Therefore if only one priority list were to be used throughout the planning period, ratio of products planned would form a discrete distribution. However, priority list used can be changed several times a day. Hence, total number of different priority lists that are used within a month is on the order of hundreds. Therefore, ratio of products planned converge to a continuous distribution for time periods considered in aggregate planning. In other words, priority lists are essential for operational level but their effects on the co-production structure diminishes as length of time period under investigation increases.
- Although the number of possible priority list configurations is finite, it is exponential in number of stacking machines and quality groups (Property 8). Therefore, the number of decision variables in priority list based composition modeling is exponential.
- The fact that only one item can be different between adjacent priority lists (Property 8) needs to be modeled in priority list based composition modeling. Determining a subset of priority lists which is "compatible" is a difficult problem and requires addition of an exponential number of binary variables to the model.

In this thesis we develop an alternative technique to model compositions. Instead of modeling production at the priority list level of detail, we consider the problem from an aggregate point of view. In **aggregate composition modeling**, quality groups and size groups are cascaded in the sense that, production decision for glass of quality group q and size group s reduces possible production of all quality groups "worse" than

q and all size groups "smaller" than s. Equation 4.13 is the composition constraint. It states that for each quality group q and size group s, ratio of production of quality groups $\{1, 2, \ldots, q\}$ and size groups $\{1, 2, \ldots, s\}$ to total production within a thickness group does not exceed R_{lqs} for each production line. R_{lqs} is a parameter, value of which is estimated statistically based on available historical data on distribution of random errors. It represents the bound imposed by random errors on ratio of possible production for a size and quality group on production a production line. Historical data about distribution of errors is available in the database of the optical laser system that detects errors on glass surface. The composition constraint is written for all quality groups, size groups, thickness groups, production lines and time periods.

$$\sum_{i:\ H(i)=h, Q(i)\leq q, S(i)\leq s} \sum_{c} X_{iclt} \leq \sum_{i:\ H(i)=h} \sum_{c} X_{iclt}\ R_{lqs} \qquad \forall (h, l, q, s, t) \tag{4.13}$$

In order to clarify the situation, we consider the hypothetical example given in Property 6. Table 4.1 shows values of R_{lqs} parameters:

	K1	**K2**
J	0.5	1.0
MS	0.75	1.0

Table 4.1. Bounds on ratio of products in the hypothetical example

On Table 4.1, it can be seen that ratio of K1/J to total production cannot exceed 0.5 due to random error distribution (Figure 2.3). Similarly ratio of K1/MS to total production cannot exceed 0.75 (Figure 2.4). In this simple example, the aggregate composition constraints would be:

$$X_{\text{K1J}} \leq 0.5\ [X_{\text{K1J}} + X_{\text{K2J}} + X_{\text{K1MS}} + X_{\text{K2MS}}] \tag{4.14}$$

$$X_{\text{K1J}} + X_{\text{K1MS}} \leq 0.75\ [X_{\text{K1J}} + X_{\text{K2J}} + X_{\text{K1MS}} + X_{\text{K2MS}}] \tag{4.15}$$

$$X_{\text{K1J}} + X_{\text{K2J}} \leq 1.0\ [X_{\text{K1J}} + X_{\text{K2J}} + X_{\text{K1MS}} + X_{\text{K2MS}}] \tag{4.16}$$

$$X_{\text{K1J}} + X_{\text{K2J}} + X_{\text{K1MS}} + X_{\text{K2MS}} \leq 1.0\ [X_{\text{K1J}} + X_{\text{K2J}} + X_{\text{K1MS}} + X_{\text{K2MS}}] \tag{4.17}$$

It can be seen that all seven compositions given in Figure 2.9 showing various alternative compositions for the hypothetical example are feasible solutions of aggregate composition constraints. In this thesis, we do not use the detailed priority list based composition modeling because the effect of priority list diminishes and ratio of products that can be co-produced converge to a continuous distribution for time periods considered in aggregate planning. Furthermore, size of the priority list based model is greater than size of the aggregate model and requires more computational resources. However, priority list based model is a closer representation of reality. We identify application of priority list based composition modeling and comparison of results obtained with results of our approach as a future research direction in Chapter 7.

Equation 11. *Nonnegativity and variable types*

Equations 4.18 and 4.19 define production duration, production quantity, inventory quantity, backlog and unsatisfied safety stock variables to be nonnegative variables. Equation 4.20 defines Y_{hlt} as a binary variable.

$$T_{iclt}, X_{iclt} \geq 0 \qquad \forall(i \in \mathcal{P}, c, l, t) \tag{4.18}$$

$$I_{ict}, B_{ict}, BS_{ict} \geq 0 \qquad \forall(i \in \mathcal{P}, c, t) \tag{4.19}$$

$$Y_{hlt} \in \{0, 1\} \qquad \forall(h, l, t) \tag{4.20}$$

4.3. Production Feasibility Set $\sigma_{\mathcal{P},\mathbf{MODE}}$

Production feasibility set $\sigma_{\mathcal{P},\text{MODE}}$ is a set which defines constraints on decision variables related to a subset of products ($\mathcal{P}$) with respect to a working mode. In other words, it defines a polyhedron on the space of decision variables corresponding to the set of feasible production plans for given products. The production feasibility set can be defined as:

$\sigma_{\mathcal{P},\text{MODE}} = \{T_{iclt}, X_{iclt}, I_{ict}, B_{ict}, BS_{ict}, Y_{hlt}\}$ such that:

$$\left\{\begin{array}{llll} \sum_i \sum_c T_{iclt} & = A_{lt} & (4.5) & \text{if MODE} = \text{STRICT} \\ \sum_i \sum_c T_{iclt} & \leq A_{lt} & (4.6) & \text{if MODE} = \text{RELAX} \end{array}\right\} \forall(l,t)$$

$$X_{iclt} = T_{iclt}\ S_{G(i)l} \qquad \forall(i \in \mathcal{P}, c, l, t) \qquad (4.1)$$

$$I_{ic(t-1)} - B_{ic(t-1)} + \sum_{l \in L(i)} X_{iclt} - D_{ict} = I_{ict} - B_{ict} \qquad \forall(i \in \mathcal{P}, c, t > 0) \qquad (4.2)$$

$$I_{ic(t-1)} \geq D_{ict}\ SS_i - BS_{ic(t-1)} \qquad \forall(i \in \mathcal{P}, c, t > 0) \qquad (4.3)$$

$$\sum_{i:\ H(i)=h} \sum_c T_{iclt} \leq A_{lt}\ Y_{hlt} \qquad \forall(h, l, t) \qquad (4.4)$$

$$\sum_{i:\ H(i)=h} \sum_c (1 - C(i))\ T_{iclt} \geq \sum_{i:\ H(i)=h} \sum_c C(i)\ T_{iclt} \qquad \forall(h, l, t) \qquad (4.8)$$

$$Y_{hlt} \geq Y_{(h+1)lt} \qquad \forall(h \geq BT, l, t) \qquad (4.9)$$

$$Y_{(h+1)lt} \geq Y_{hlt} \qquad \forall(h < BT, l, t) \qquad (4.10)$$

$$\sum_{i:\ H(i)=h} \sum_c T_{iclt} \geq MD_h\ Y_{hlt} \qquad \forall(h, l, t) \qquad (4.11)$$

$$\sum_{i:\ S(i)=s} \sum_c X_{iclt} \leq A_{lt}\ SC_{ls} \qquad \forall(l, s, t) \qquad (4.12)$$

$$\sum_{i:\ H(i)=h, Q(i) \leq q, S(i) \leq s} \sum_c X_{iclt} \leq \sum_{i:\ H(i)=h} \sum_c X_{iclt}\ R_{lqs} \qquad \forall(h, l, q, s, t) \qquad (4.13)$$

$$T_{iclt}, X_{iclt} \geq 0 \qquad \forall(i \in \mathcal{P}, c, l, t) \qquad (4.18)$$

$$I_{ict}, B_{ict}, BS_{ict} \geq 0 \qquad \forall(i \in \mathcal{P}, c, t) \qquad (4.19)$$

$$Y_{hlt} \in \{0, 1\} \qquad \forall(h, l, t) \qquad (4.20)$$

4.4. Campaign Planning

Colored glass is produced in campaigns in order to minimize high color changeover time and cost (Property 14). An important observation is that the aggregate planning problem is decomposable over colors. The reason for this is that glass of each color is produced independently and products with different colors have no interaction such as compositions, thickness changeovers etc. except being produced on the same production line on different days. Therefore, products with different colors can be planned in sequential phases by updating available capacities of production lines after each phase. In our decision support system, decision makers give the start time of campaigns, colors to be produced within each campaign along with associated changeover time in a format similar to Table 4.2:

Line	**Code**	**Start Period**	**Sequence**	**Color**	**Changeover**
PL1	Campaign1	1	1	Color1	3
	Campaign1		2	Color2	4
	Campaign1		3	Color3	6
PL1	Campaign2	5	1	Color1	3
	Campaign2		2	Color4	5

Table 4.2. Sample sequence of campaigns

It can be seen that there are two color campaigns: Campaign1 is expected to start at the beginning of period 1 on production line PL1. Color1, Color2 and Color3 will be produced in given sequence. Associated changeover times are given in the last column. After Campaign1, clear glass will be produced until period 5 at the beginning of which Campaign2 will start. Campaign2 consists of production of Color1 and Color4.

Although determining timing and sequence of campaigns automatically is not difficult (Property 14), letting decision makers plan the sequence and timing of campaigns allows them to have more control over the optimization system. However, calculating optimal duration and product mix of campaigns is a difficult optimization problem and is tackled by our decision support system. In the example given, Color2, Color3 and Color4 are produced only once. Demand of entire planning period needs to be satisfied in a single production run for those colors. The minimum production duration and product mix for satisfying entire demand under production constraints needs to be found. The situation is more complicated for Color1: it is to be produced twice throughout the year. In the first campaign, entire demand up to period 5 needs to be satisfied at minimum production time and rest of the demand needs to be satisfied within the second campaign. However, production within the first campaign that is in excess of demand needs to be planned carefully as well. It is desired that these co-products that are carried in inventory can be used to satisfy demand after period 5 so that inventory costs are minimized. Another benefit of this is a reduction in demand to be satisfied from production within second campaign, resulting in a shorter production duration for the second campaign.

Model 1. *Campaign planning*

The mathematical model used for planning campaigns for products of a particular color R:

$$min \quad \sum_i \sum_c \sum_t (h_{ic}\ I_{ict} + b_{ic}\ B_{ict}) + \sum_i \sum_c \sum_l \sum_t (X_{iclt}\ P_{lt}) \tag{4.21}$$

$$s.t. \quad \{T_{iclt}, X_{iclt}, I_{ict}, B_{ict}, BS_{ict}, Y_{hlt}\} \in \sigma_{\mathcal{P}=\{p:R(p)=R\},\text{RELAX}} \tag{4.22}$$

Here, P_{lt} variables denoting preference of producing on production line l at time period t are initialized in the following way: P_{lt} values for time periods in which a campaign is designated to begin are set to be 0. P_{lt} values for other time periods are set in an increasing way. For example in the example given regarding Color1, $P_{21} = P_{25} = 0$, $P_{22} = P_{26} = 1$, $P_{23} = P_{27} = 2 \ldots P_{212} = 11$ etc. P_{lt} values for all other production lines and/or time periods are set to be an arbitrary large value M. For example, in the same example $P_{11} = P_{31} = P_{41} = P_{12} = P_{32} = \cdots = M$. Under this setting, production feasibility set guarantees feasibility while structure of the objective function guarantees the following properties:

- All demand is satisfied due to the high penalty term on backlogs.
- Campaign durations are minimized due to penalty term on inventory carried. The feasible region is defined by the the production feasibility set in RELAX mode. In other words, full utilization of production lines is not enforced. Therefore, the penalty on inventory carried guarantees that no extra inventory which could be eliminated without violating other constraints such as composition and thickness changeover constraints is carried in the optimal solution. Therefore, minimum campaign duration is found in the optimal solution.
- Production is planned as early as possible within campaigns. The structure of

P_{lt} variables means that it is more preferable to produce early within a campaign rather than late. Therefore production for a later time period is not planned unless the production lines are fully utilized in earlier time periods.

Given the campaign planning model (Model 1) which finds optimal production plan for glass of any color, it can be used within an algorithm for planning all campaigns.

Algorithm 1. *Campaign planning*

Initialize: Sort colors in ascending order of beginning of first campaign and sequence

for all Color R **do**

  for all Production line l, Time period t **do**

    $A_{lt} \leftarrow A_{lt}-$(changeover time)

    Initialize P_{lt} parameter

  end for

  Apply Model 1 to obtain the optimal production plan for color p

  for all Production line l, Time period t **do**

    $A_{lt} \leftarrow A_{lt} - \sum_i \sum_c T_{iclt}$

  end for

end for

4.5. Multi-Site Aggregate Planning

Model 2. *Multi-site aggregate planning*

Clear glass ($R = 0$) is planned after color campaigns by the following mathematical model:

$$\begin{aligned} min \quad & \sum_i \sum_c \sum_t (h_{ic}\ I_{ict} + bs_{ic}\ BS_{ict} + b_{ic}\ B_{ict}) \\ + \quad & \sum_i \sum_c \sum_l \sum_t \left(X_{iclt}\ TC_{clS(i)}\right) \end{aligned} \tag{4.23}$$

$$s.t. \quad \{T_{iclt}, X_{iclt}, I_{ict}, B_{ict}, BS_{ict}, Y_{hlt}\} \in \sigma_{\mathcal{P}=\{p:R(p)=0\},\text{STRICT}} \tag{4.24}$$

The objective function (Equation 4.23) aims to balance multiple objectives (Property 17):

- Satisfying demand by penalizing backlog on demand
- Minimizing transportation costs
- Satisfying safety stocks by penalizing backlog on safety stock
- Minimizing inventory carrying costs

in decreasing order of priority. Feasible region is defined by $\sigma_{\mathcal{P}=\{p:R(p)=0\},\mathrm{STRICT}}$. Hence remaining available time after campaigns on all production lines is fully allocated to clear glass. Therefore if demand is more than available capacity, clear glass is made to stock instead of colored glass, parallel to the policy employed by decision makers.

Algorithm 2. *Multi-site aggregate planning*

Run Algorithm 1 to plan color campaigns

Apply Model 2 to obtain the optimal production plan for clear glass

An implicit assumption in Algorithm 2 is that satisfaction of colored glass demand is preferred to satisfaction of clear glass demand. Assume that total demand is too high so that it cannot be met by available capacity. Algorithm 2 first plans colored glass and allocates remaining capacity to clear glass. Therefore in this case, entire demand for colored glass is satisfied and some demand for clear glass is backlogged. This assumption is based on two observations:

- On the average colored glass is more profitable than clear glass.
- Demand for approximately 60 % of colored glass originates from the automotive industry with which long term contracts are made.

4.6. Strategic Planning

There are two main decisions that need to be given before tactical planning phase due to long lead times involved (Property 16):

- Timing, location, capacity and production capabilities of new facilities to be built
- Amount and distribution of export sales

Strategic planning is carried out for a horizon of seven to ten years through yearly time periods. Our decision support system is used by decision makers for evaluation of alternative capacity expansion policies.

The marketing strategy employed by Şişecam is satisfaction of entire domestic demand and allocating remaining production capacity to exports (Property 16). Marketing resources are allocated in accordance with the marketing strategy and long term logistics capacity allocations are based on the export strategy. Therefore, amount and distribution export sales to foreign markets is a strategic decision. One possible way of giving export decisions could be optimizing production for satisfaction of domestic demand and giving export decisions based on remaining capacity. However, decomposing domestic and export sales decisions in two phases produces inferior results: domestic demand is allocated to nearby facilities in order to minimize transportation costs in domestic phase without consideration of transportation costs imposed by export sales. Therefore, domestic and export sales need to be considered simultaneously in an optimization model where domestic sales are parameters and export sales are decision variables.

Objective function of Model 3 used for strategic planning is the same as the one of Model 2, aiming to satisfy all demand and minimize transportation costs. Equation 4.26 ensures that ratio of product i sold to export customer c to total export sales is a fixed ratio DR_{ic} given as a parameter. This parameter is a representation of higher level marketing strategic decisions regarding target market shares in foreign markets. Equation 4.27 defines foreign demand variables as nonnegative and Equation

4.28 defines production feasibility constraints for all products. It should be noted that color campaigns are not considered explicitly in strategic planning since the time period is a year, much longer than campaign durations.

Model 3. *Strategic planning*

The mathematical model used for strategic planning is given in the following formulation:

$$min \quad \sum_i \sum_c \sum_t (h_{ic}\ I_{ict} + bs_{ic}\ BS_{ict} + b_{ic}\ B_{ict}) + \sum_i \sum_c \sum_l \sum_t (X_{iclt}\ TC_{clS(i)}) \quad (4.25)$$

$$s.t. \qquad D_{ict} = DR_{ic} \sum_i \sum_c D_{ict} \quad (\forall i \in \mathcal{P}, c : E(c) = 1, t) \quad (4.26)$$

$$D_{ict} \geq 0 \quad (\forall i \in \mathcal{P}, c : E(c) = 1, t) \quad (4.27)$$

$$\{T_{iclt}, X_{iclt}, I_{ict}, B_{ict}, BS_{ict}, Y_{hlt}\} \in \sigma_{\mathcal{P}=\{p\},\text{STRICT}} \quad (4.28)$$

5. IMPLEMENTATION USING ICRON

The system has been implemented on ICRON version 2 [26]. ICRON is an object oriented algorithm modeling system. It has an integrated component for visual algorithm development on which almost any algorithm that can be implemented in a general purpose programming language such as C++ can be modeled. Using ICRON, algorithms are developed by dragging "node"s and connecting them together in a way that resembles flow charts commonly used in software system design. However, there's a fundamental difference between flowcharts and ICRON algorithms: flowcharts are just visual representations of algorithms while ICRON algorithms are executables themselves.

ICRON has mechanisms for integration with any data source including databases, XML files, web services etc. Furthermore, it has constructs for development of scheduling algorithms. Mathematical modeling capabilities have been added in the second version [27]. The key issues in ICRON regarding mathematical modeling are [28]:

- *Data model is object oriented:* ICRON represents data as objects and relationships between objects unlike the traditional vector and matrix form used in algebraic modeling tools such as GAMS [29], LINGO [30], AMPL [31] etc.
- *Mathematical model is object oriented:* Objective function and constraints are written directly on the object oriented data model in a unique modeling language with object oriented, index-free syntax. This allows for easier mapping of business model into mathematical model.
- *Mathematical model is built and executed within an algorithm:* Unlike traditional mathematical modeling tools in which mathematical model is written into a text file and interpreted by the software with little space for algorithmic constructs, the entire mathematical modeling process is algorithmic in ICRON. It is possible to develop algorithms that read data from several data sources, manipulate the data, define an optimization problem using the data, solve the optimization problem and continue execution with the optimal result.

- *Decision variables and parameters are weakly separated:* In traditional mathematical modeling process the very first step is identification of decision variables and parameters. Constraints and objective function are modeled *given* choice of decision variables and parameters. Traditional mathematical modeling tools follow the same route. However in ICRON, mathematical model is developed *independent* of decision variables and parameters. Decision variables can be designated at any stage before solution. Therefore, the same mathematical model can be used in several optimization problems with different choices of decision variables. This feature facilitates reuse in mathematical modeling and we use it extensively in implementation of the production feasibility set (Section 4.3) and in strategic planning where demand for domestic markets is parameter while demand for foreign markets is decision variable (Section 4.6).

5.1. Object Oriented Data Model

Figure 5.1 is a UML class diagram representing the classes and their relationships. Description of the classes:

- **ProductGroup** represents a product group. It has the attributes *Color*, *Coating* and *Thickness* and relations to products within this product group and production speeds of this product group on production lines on which it can be produced.
- **Product** represents a product. It has relations to the product group, size and quality groups this product is a member of, customer it is shipped to and periods it can be produced in.
- **Line** represents a production line. It has relations to the product group and speeds this production line can produce, freight costs for products it can produce and periods it can make production in.
- **Customer** represents a customer. It has relations to the products the customer demands and associated freight costs.
- **Size** represents a size group. It has relations to the products of this size and freight costs for transporting glass of this size from production lines to customers.
- **Quality** represents a quality group. It has relations to the products within this

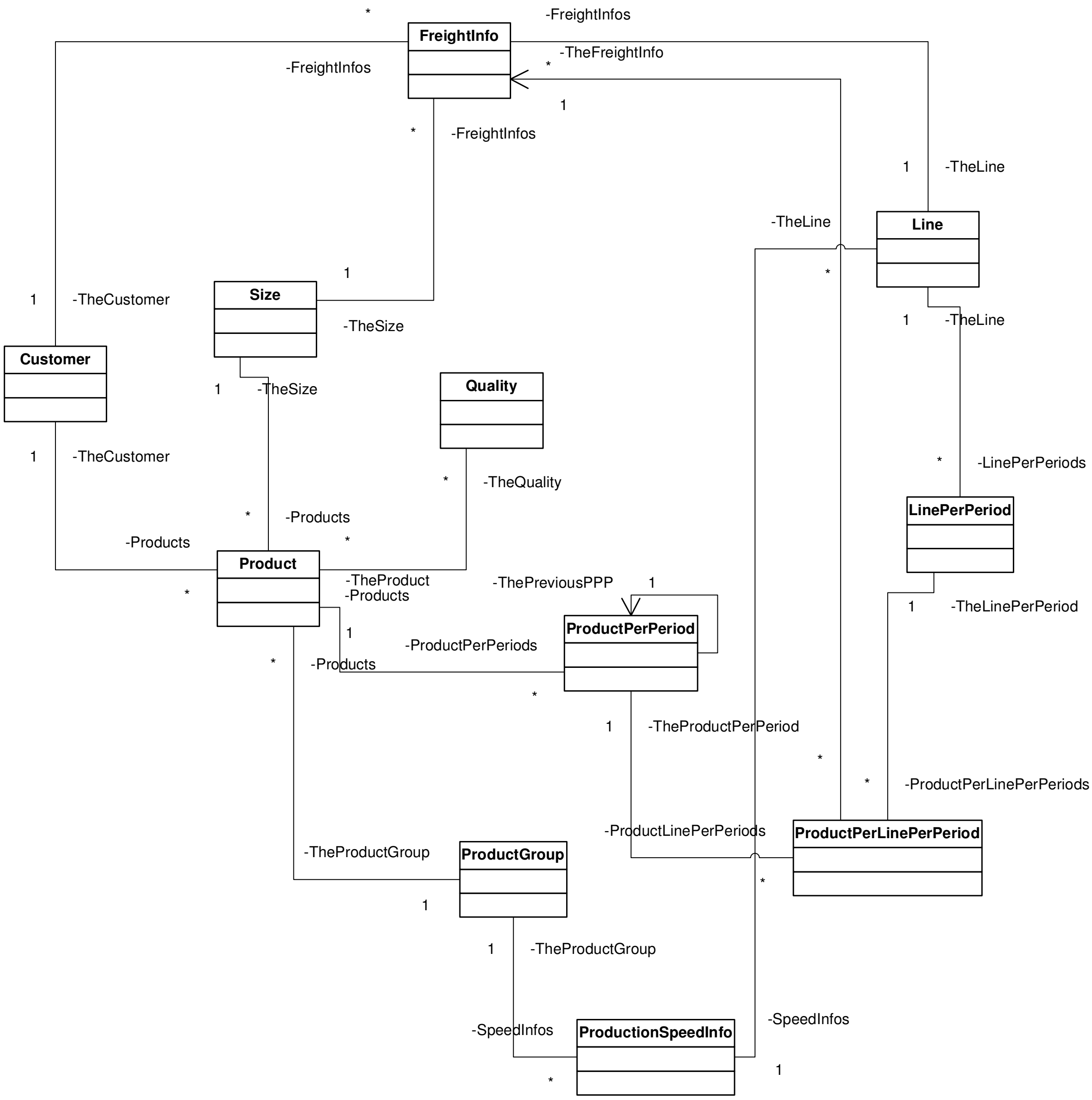


Figure 5.1. UML class diagram of the system

quality group.

- **FreightInfo** holds transportation cost incurred when glass within a particular size group is transported from a production line to a customer.
- **ProductionSpeedInfo** holds production speed of a particular product group on a production line.
- **ProductPerPeriod** contains information about a particular product in a specific time period. The class has the attributes *InventoryQuantity*, *UnsatisfiedSafety-Stock* and *Backlog*. Furthermore it has relations with production of the product on all production lines and the object containing information about the same

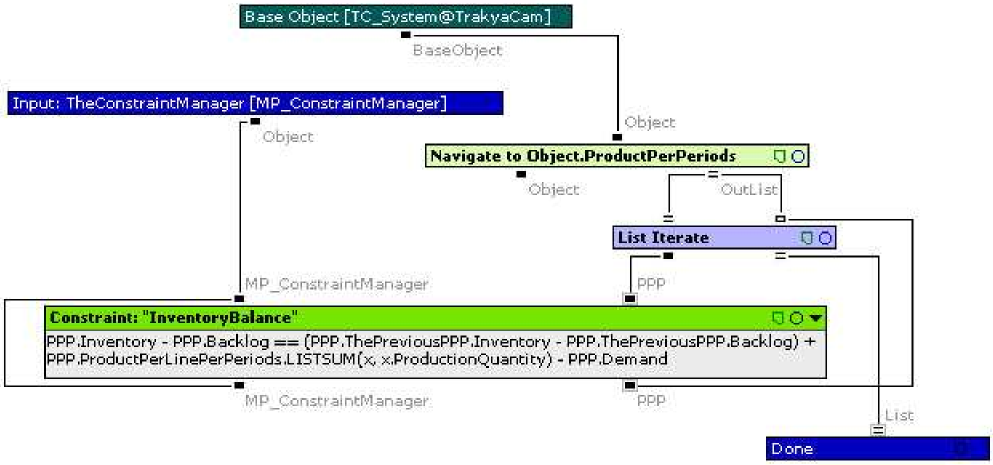


Figure 5.2. Inventory balance constraint in ICRON

product in the previous time period.

- **LinePerPeriod** contains information about a particular production line in a time period. It has the attribute *AvailableTime* and it has relations with all products that can be produced on this line in this period.
- **ProductPerLinePerPeriod** contains information about production of a particular product on a production line in a time period. It has the attributes *ProductionDuration* and *ProductionQuantity*.

5.2. Mathematical Model in ICRON

In this section we give examples of ICRON algorithms used for modeling some constraints. Figure 5.2 is a screen shot from ICRON showing the algorithm in which the inventory balance constraint (Equation 4.2) is modeled. The constraint is written for all products and time periods. In the ICRON algorithm, the **Navigate** node returns a list of all ProductPerPeriod objects. The node **ListIterate** defines an iteration for all objects in this list and the node **Constraint** is executed once for each element in the list. Each time the **Constraint** node is executed, inventory balance constraint for a particular product and time period is created and the algorithm ends when all inventory balance constraints have been created.

Similarly, Figure 5.3 is a screen shot of the algorithm in which the coating con-

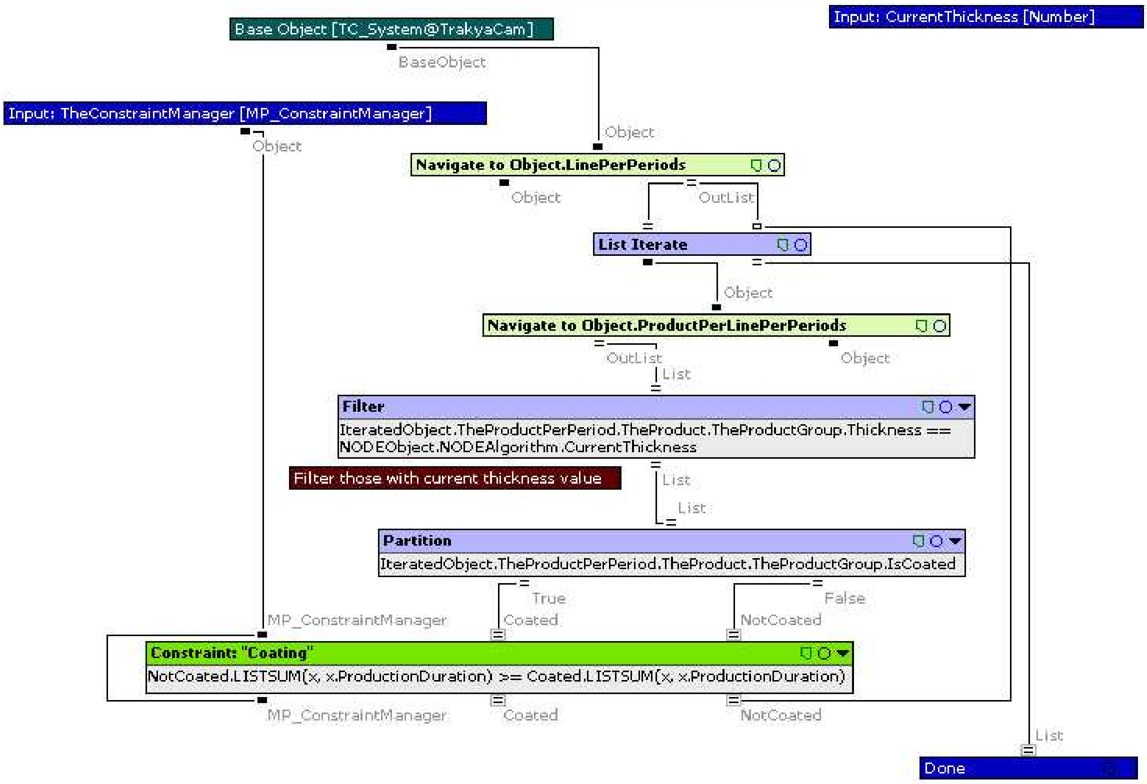


Figure 5.3. Coating constraint in ICRON

straint (Equation 4.8) is modeled. The constraint is written for all production lines, thickness groups and time periods. The constraint models the fact that coated glass can only be produced during daytime (Property 4). The first **Navigate** node returns a list of all LinePerPeriod objects and the node **ListIterate** defines an iteration on this list. The second **Navigate** node returns a list of ProductPerLinePerPeriod objects that correspond to all products that can be produced on a particular line in a particular period. The **Filter** node filters those products within a thickness group and The **Partition** node partitions the list into two subsets based on type of their coating. Finally the **Constraint** node creates the coating constraint. Note that the expression *NotCoated.LISTSUM(x, x.ProductionDuration) >= Coated.LISTSUM(x, x.ProductionDuration)* translates naturally into "total production duration for not coated glass must be greater than or equal to total production duration for coated glass".

5.3. Information Systems Involved in Implementation and Flow of Data

Figure 5.4 is a visual representation of information systems involved in implementation of our decision support system and the flow of data.

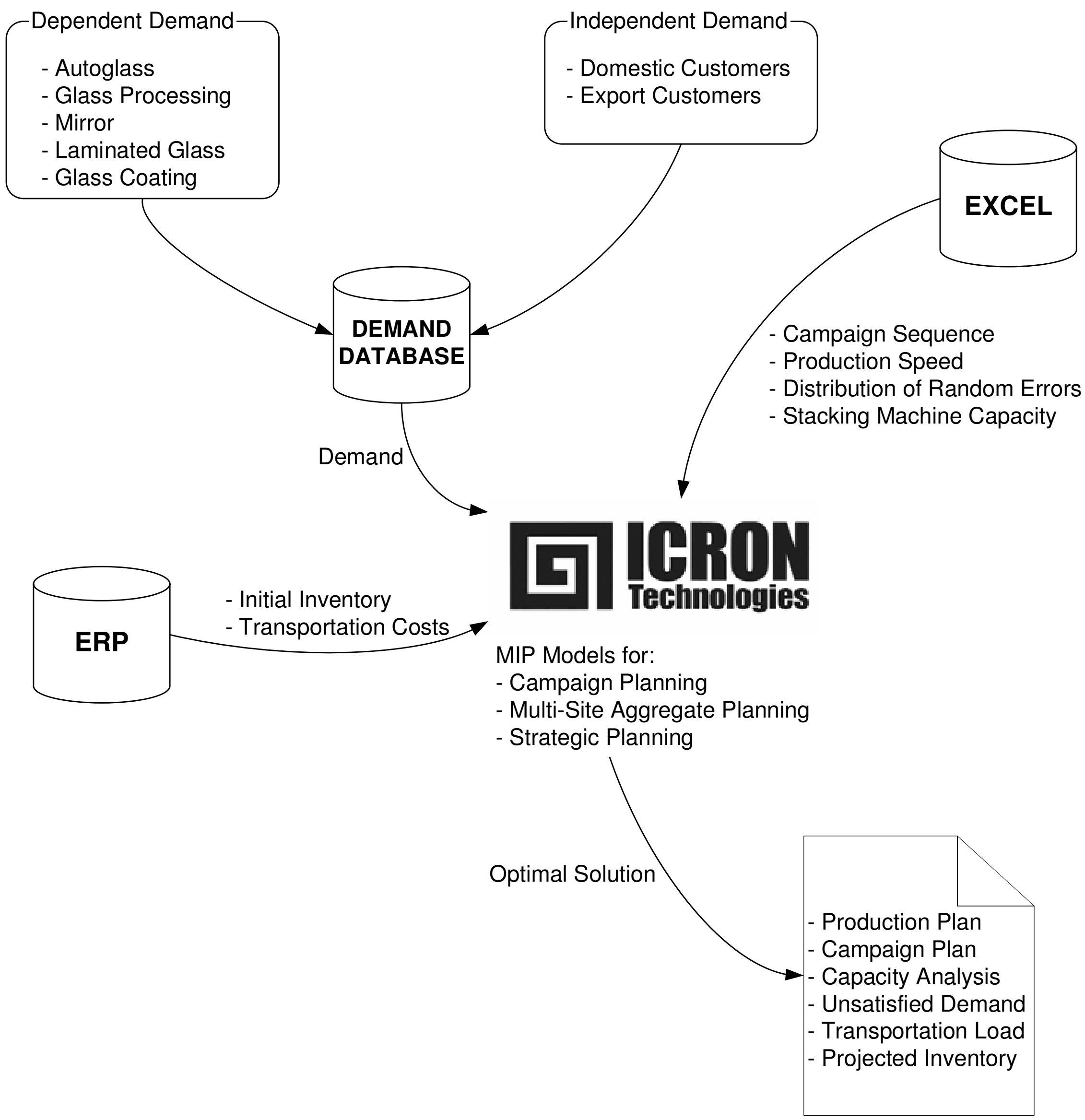


Figure 5.4. Information systems involved in implementation and flow of data

Demand data is a combination of forecasts from various sources:

- *Dependent demand:* Trakya Cam has several facilities that produce different types of flat glass products including automotive glass, processed glass, mirror glass, laminated glass and coated glass (Chapter 1). All of these facilities use float glass as their main raw material. Therefore float glass facilities are suppliers for those. Aggregate production plans of these facilities are made based on their own independent demand and production capacities. Later, float glass requirements for those facilities are calculated and are considered as dependent demand by our decision support system.

- *Independent demand:* Trakya Cam sells float glass to customers in domestic and foreign markets. Forecasting and handling of independent demand is different in strategic planning and tactical planning:
  - *Strategic planning:* During strategic planning, the marketing strategy employed by Trakya Cam is satisfying entire domestic demand and allocating remaining production capacity to export sales (Property 16). In accordance with this strategy, our decision support system optimizes capacity allocation to balance between domestic and export sales during strategic planning. In other words, domestic sales is an input for our strategic planning model while export sales is an output (Section 4.6).
  - *Tactical planning:* During tactical planning, sales department estimates annual sales forecasts for domestic and foreign customers and planning department disaggregates this figure into monthly, product and customer based forecasts by considering the previous year's realized sales data. Therefore, sales forecasts mimic the distribution of previous year's sales and are adjusted so that the total is in accordance with the aggregate forecast given by sales department. Although this approach results in realistic forecasts, it is "passive" in the sense that sales forecasts are taken as a given fact and production is planned based on satisfaction of forecasted demand. Contrarily an "active" approach could be determining the most profitable sales strategy based on production capacity. This point is further discussed in Chapter 7.

Information regarding transportation costs and available inventory levels for products are retrieved from the ERP system used at Trakya Cam. Actual transportation costs are used for existing facilities and customers while freight costs for potential facilities are estimated during strategic planning. Data that is not available in the ERP such as estimated distribution of random errors (Property 6) and data that is available but not regularly updated such as production speed of products on alternative production lines (Property 2) is read from Excel files. Furthermore, colored glass campaign sequence is given by decision makers on an Excel file as discussed in Section 4.4.

Our decision support system implemented on ICRON retrieves data from those sources in relational database format, constructs an object oriented data model (Section 5.1), runs Campaign Planning (Section 4.4), Multi-Site Aggregate Planning (Section 4.5) or Strategic Planning (Section 4.6) algorithms. These optimization algorithms are based on mixed integer programming models (Chapter 4). The mathematical programs are constructed in system memory and solved by solvers. Unlike other traditional modeling tools that just write the solution to a text file, ICRON stores optimal solutions in objects residing in system memory which are accessible for further manipulation. Several reports such as optimal campaign plan, production plan for each production line and facility, projected inventory level for each product and product group are prepared on-the-fly and are accessible by any computer on the network. Furthermore, reports for analyzing how much capacity is allocated to satisfy forecasted demand, how much capacity is used for production to stock and how much demand is backlogged etc. are available. These reports can also be exported to Excel for further analysis.

Although the system can be executed at any time with current inventory levels for products, in practice it is used on a monthly basis. Length of time periods for tactical planning is one month while it is one year for strategic planning. Tactical planning system is used on a rolling horizon basis. In the beginning of each month, sales forecasts are updated if necessary and the system is executed with current inventory levels. Current inventory levels reveal summarized information about realized production and sales during previous periods. Planning horizon for tactical planning is twelve months and six to eight years for strategic planning.

6. RESULTS

In order to examine functionality and correctness of the system, the system has been tested using inventory status of products at the beginning of 2005 and monthly sale forecasts for a time period of 12 months. The results have been compared to the production plan prepared manually by production planning staff. The staff have been using custom designed spreadsheets on Excel for production planning. Formulas on the spreadsheet are mainly used for error checking purposes and decision making is completely manual. Since the same data set used for manual planning has been used for testing our decision support system, the results are comparable. Main differences between results obtained are:

Result 1. *Complexity of production planning at individual product level of detail can be handled.*

Production planning is based on color, thickness and coating of glass in manual production planning. Size and quality are not considered. The main reason for this is reducing dimensional complexity in order to keep the problem at a manageable size for the decision maker. On the other hand, our decision support system is based on products and handles the additional complexity.

Result 2. *Complexity of production planning at individual customer level of detail can be handled.*

Another simplification made during manual production planning is grouping several customers into a few customer groups. For example, even though Trakya Cam exports to more than 20 countries worldwide, all foreign markets are treated as a single customer group. Similarly all local customers except other Trakya Cam facilities (Chapter 1) are grouped together. In contrast, individual customers can be modeled in our system.

Result 3. *Detailed conditions on composition and demand substitution issues are con-*

sidered adequately.

Composition (Property 13) and product substitution (Property 12) involve complex relationships between products. Since it is difficult to consider those in manual planning, planning staff make the production plan at product group level (Result 1) and do not consider those issues explicitly. Instead, they rely on their experience about feasibility of the plan in terms of compositions. However, comparison of production plans created manually and by our decision support system has revealed some infeasibilities in the manual production plan regarding compositions. This is especially the case for some types of colored glass in which demand is quite small compared to clear glass. In one case, more than 70% of colored glass demand is for quality group K1, which is of highest quality level. However, it is not possible to produce K1 quality glass without accompanying glass of lower quality levels due to the composition issue (Property 13). Investigation of the manual production plan has revealed that the amount of planned production is roughly equal to demand for glass of this color, meaning that co-production of lower quality glass has not been planned and hence the composition constraint has been violated.

Result 4. *Color campaigns are planned in detail subject to production constraints.*

Colored glass is produced in one or two campaigns each year and campaign planning is crucial for inventory management of colored glass (Property 14). Furthermore since demand for colored glass is relatively small, composition issues are more relevant in production of colored glass compared to clear glass. Campaign plans prepared manually and by our decision support systems have been compared and the following observations have been made:

- Campaign durations for some colors are less than necessary duration required to produce for demand in subsequent time periods. The main reason for this is that composition issues have been disregarded in manual planning (Result 3). Although total amount of colored glass produced is roughly equal to total demand, it is not possible to satisfy demand of high quality glass without extending campaign duration and producing some glass of lower quality groups as well.

- On the other hand, durations for some campaigns are more than the sufficient duration. This is especially the case for colors for which more than one campaigns are defined. The main reason seems to be that, planners cannot optimize compositions in the first campaign so that byproducts of the first campaign are required productions for the second campaign. This results in excess inventory resulting from the first campaign and extended duration for the second campaign for production of glass that could have been produced in the first campaign.

Result 5. *Conditions on thickness changeovers and minimum production durations are enforced.*

Thickness changeover has to be performed gradually in float glass production (Property 5). However, investigation of the production plan prepared manually has revealed some inconsistencies regarding thickness changeovers: for example for a month production for thickness groups 4 mm and 6 mm have been planned but no production for the groups 4.2 mm, 5 mm or 5.5 mm has been planned. In contrast, our decision support system contains constraints that enforce conditions on thickness changeovers (Section 4.2.2).

Result 6. *Total production quantity and inventory levels are 2% lower than the ones in manual planning.*

Upon comparison of total production quantities, the figure for manual production plan has been found to be approximately 2% more than the one for our decision support sysem. This result suggests that human decision makers tend to choose faster production lines for alternative selection (Property 2). However, since entire demand can already be satisfied by our result, the additional 2% is stored in inventory.

Result 7. *Freight costs are considered explicitly, leading to 10% decrease in transportation costs.*

Since considering transportation costs explicitly is difficult in manual production planning, decision makers use simple rules based on past experience for assignment of customer demands to facilities. Furthermore since production planning is based on aggregate customer groups instead of individual customers, it is not possible to consider distance information for individual customers. However, our decision support system considers transportation costs explicitly and customer demands are defined in a more detailed level. Total transportation cost for the manual production plan has been calculated and compared to the figure for the production plan created by our decision support system. The results indicate an improvement of about 10% corresponding to an estimated \$5.000.000 saving in annual transportation costs without any loss in quality of service.

7. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

In this work a mixed integer linear programming based decision support system for solving tactical and strategic level central planning problems regarding float glass manufacturing in a multi-site environment faced at Trakya Cam is introduced. Float glass is manufactured in a continuous process and unique characteristics of the process such as co-production, random yields and substitutable products complicate planning. Furthermore, production speed varies significantly between products and production lines. Hence, production capacity depends considerably on product mix. There are multiple facilities that are geographically diverse and transportation costs are significant. Therefore, capacity planning and optimization is important for efficient operation of the firm. In this thesis, float glass manufacturing process is described in detail with special emphasis on planning issues.

We model characteristics of the process and complex relationships between products under some simplifying assumptions. For this purpose, we first develop a production feasibility set which defines process related properties as mixed integer linear constraints. Then we use the set as a black-box to tackle several problems in tactical and strategic level planning:

- *Campaign planning:* Since color changeover times and costs are very high, colored glass is produced in campaigns. Determination of timing, duration and product mix of campaigns is a difficult optimization problem which we solve by application of a mixed integer linear program within an algorithm.
- *Multi-Site production planning:* Trakya Cam has multiple production facilities with different production capacities that serve customers worldwide. We define the problem of planning production in multiple facilities so that transportation costs are minimized as a mixed integer linear programming model.

- *Strategic planning:* Timing, location and capacity of new investments seriously affect future profitability. Furthermore, allocation of production capacity between multiple markets is an issue in strategic planning. We develop a mathematical model for strategic planning and long term demand planning.

Following mathematical model development, we discuss implementation issues. The decision support system described in this thesis has been fully implemented using ICRON and has been deployed for use by central planning department of Trakya Cam. Comparison of the decision support system with results obtained by manual planning aided by a simple spreadsheet based application previously used reveals some important contributions of our work:

- *A higher level of dimensional complexity is handled:* Manual planning is based on product groups and customer groups while our system easily handles several products and individual customers, resulting in a more detailed production plan.
- *More detailed production constraints are considered in planning:* Some important properties of production which are difficult to handle are not considered explicitly during manual planning. This results in infeasibilities in resulting production plan. Those constraints are modeled explicitly in our decision support system. Therefore our system works on a closer representation of reality and produces results which are applicable in the real production environment.
- *Freight costs are considered explicitly:* Allocation of customer demand to facilities is based on simple, experience based rules in manual planning. However, our decision support system optimizes transportation costs while ensuring feasibility. This results in a 10% decrease in transportation costs corresponding to an estimated $5.000.000 annual improvement with no decrease in quality of service.

The system described in this thesis, beside solving solving some important planning problems faced in float glass manufacturing, provides an infrastructure on which further applications can be based:

- *Operational planning and scheduling:* In the operational environment, process quality and error density changes continuously. A scheduling system integrated with the the optical laser system could be designed. The scheduling system could track the production process and control stacking machine compositions and cutting policy so that production plans determined by our higher level planning system can be realized.
- *Scenario based strategic planning:* The strategic planning system could be extended to account for several scenarios regarding demand, capacity, transportation costs. Stochastic programming techniques could be adapted for this purpose.
- *Planning for cross-sales:* Some industries such as automotive industry require tight specifications on glass products in terms of quality and thickness. Tolerances for some other applications such as construction industry are less strict. In our model, we consider product substitution regarding quality level within the same size and thickness group. However, demand for some products can also be substituted by products with close thickness values. For example, some customers demanding glass of thickness 2.5 mm might equally be satisfied with glass of thickness 2 mm or 3 mm. 3 mm glass can be produced approximately 4% faster than 2.5 mm glass and 8% faster than 2 mm glass. However, raw material requirement for 3 mm glass is higher than those for 2.5 mm and 2 mm glass. Therefore, marginal costs for products with different thickness values are different. Thickness changeover also has associated costs. Furthermore, some error is introduced in the forecasting process while disaggregating total sales forecast down to individual thickness values. Therefore reducing number of thickness groups produced could be beneficial and an interesting research topic would be identification of thickness groups at which production should be done for optimal performance. Similarly, our decision support system could be extended to consider product substitution opportunities between different thickness groups.
- *Demand planning:* Sales department gives an annual aggregate sales forecast for domestic customers and planning department disaggregates this figure into monthly, product and customer based forecasts by using the previous year's realized sales data. Therefore forecasts are based on what *was* sold previously and an aggregate goal. Later, our system is used for optimizing production so that

forecasts are met. However, the problem could be considered from the opposite direction: what *should* be sold given production capabilities? Given sales prices of products, unique characteristics of production environment, cross-sales opportunities and marketing goals; products that *should* be sold for the most profitable operation could be analyzed.

Some other approaches to the planning problem could also be formulated:

- *Priority list based composition modeling:* In this work, we model the composition issue as aggregate constraints on products that limit production due to random errors. A more detailed model, closer to operational level which is based on assigning production times to individual compositions could be developed (Section 4.2.2). Since the number of possible compositions is finite but exponential, such a model would require more computational power and might require application of column generation techniques. Results obtained by our high level approach and the low level composition based approach could be compared to see whether increased complexity and resource requirements of composition based approach is justifiable.
- *Stochastic optimization:* The production process has inherent stochasticity which we model by using statistical estimates on available data. An entirely different approach could be modeling the process using stochastic optimization techniques. For example, compositions could be modeled as the state space of a Markov chain since duration of production within a composition is a random variable due to random errors on glass surface. In this case, change in composition would correspond to a transition in the Markov chain. More research is required in this area.

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